

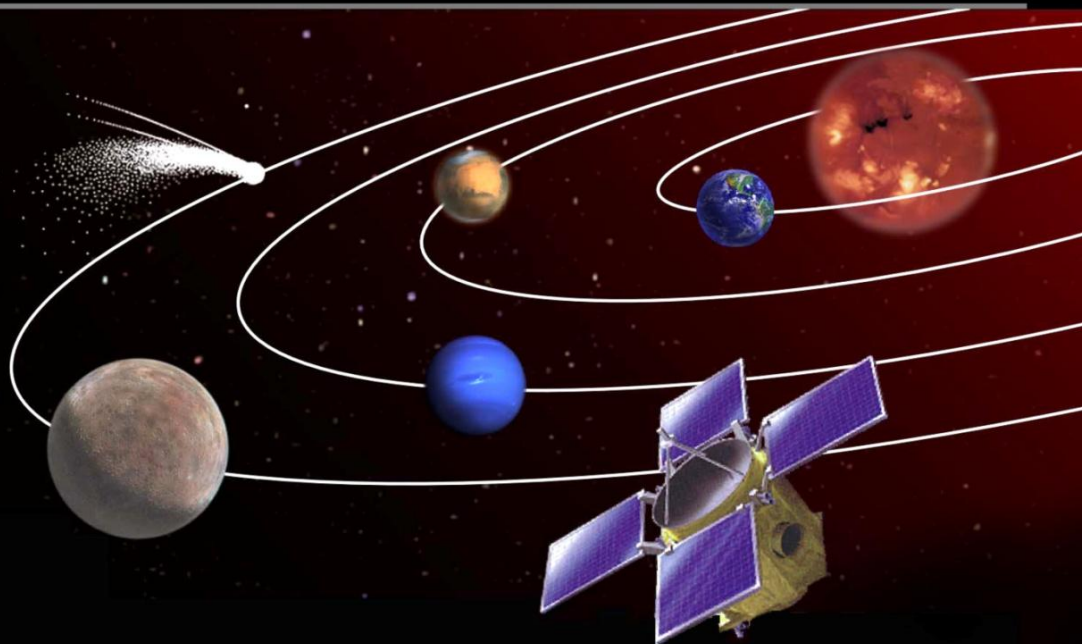
Proceedings

National Aeronautics and
Space Administration



Discovery Science Workshop

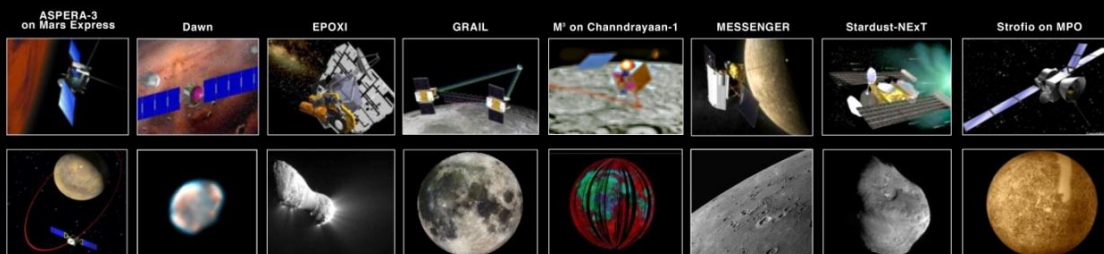
December 1-2, 2010



Westin Washington, D.C. City Center Hotel

**Hosted by: NASA Science Mission Directorate,
Planetary Science Division,
Discovery Program**

Current Discovery Missions:



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1.0 Executive Summary

The NASA Science Mission Directorate, Planetary Science Division's Discovery Program hosted a "Discovery Science Workshop" on December 1-2, 2010 at the Westin Washington DC City Center Hotel.

The focus of the workshop was sharing information and lessons learned related to science planning, science implementation, and science data archive between the current Discovery projects.

Four of the ongoing Discovery missions provided briefings on the status and processes for science planning, implementation and data archiving. The workshop identified some flight operations-related lessons learned from past and current robotic missions that can be applied to future missions in planetary science. The mission briefings presented during the workshop are provided in their entirety as Appendices 5-8.

In addition to the invited briefings, there was an open forum during the workshop. Representatives from the other Discovery missions were allowed to provide verbal summaries of lessons learned and their past and current approach to mission science implementation issue resolution.

Neither the workshop's invited speakers nor this proceedings document identifies specific recommendations to be applied to current or future Discovery mission implementation. However, each mission that presented (MESSENGER, Stardust-NExT, GRAIL, and Dawn) during the workshop identified common themes and general lessons learned from their past experience either verbally or in their briefing charts. This proceedings document is the tool for making the information available to both current and future Discovery missions. Other planetary science missions in other programs may also benefit from the general knowledge captured by these selected Discovery missions.

The NASA Science Mission Directorate, Planetary Science Division sponsored the workshop. Approximately thirty-five participants attended the workshop. The attendees included Division Directors, Mission Principal Investigators, Program Executives, Mission Managers, Program Directors, Program Integration Managers, and Program and Mission engineering and science technical staff. Representatives from current missions in the Lunar Quest Program also attended the workshop.

Participants generally agreed the workshop was valuable and there was an informal consensus that NASA should conduct future workshops on this topic. The next Discovery Science Workshop will be convened in 2012.

2.0 Introduction

Currently, there are eight active Discovery Full Missions and Missions of Opportunity (MOs). The individual projects are managed by both NASA government organizations and non-government organizations such as university-affiliated and commercial research laboratories. The current Discovery missions along with their Principal Investigator's home organization and mission type are shown in Table 2.0-1. All eight current missions were represented at the workshop as well as some completed missions.

Because the Discovery missions are not coupled and are conducted by unrelated organizations, there is no need for mission integration at the program level. However, there are similarities in mission type and operational approaches across the various missions that allow for the sharing of past experience and lessons learned. This workshop was convened to share that information and lessons learned across the Discovery missions. These proceedings integrate the information provided by the individual projects into a single package which is a resource for both current and future planetary science projects.

Table 2.0-1 Current Discovery Missions

Mission Name	Mission Acronym	Principal Investigator Organization	Mission Type	Solar System Target	Mission Phase
Extrasolar Planet Observation and Characterization with Deep Impact Extended Investigation	EPOXI	University of Maryland	MO	Comet and Extrasolar	Science Operations
Stardust - New Exploration of Tempel-1	Stardust-NExT	Cornell University	MO	Comet	Science Operations
Moon Mineralogy Mapper	M ³	Brown University	MO	Moon	Post Mission Data Analysis
Analyzer of Space Plasmas and Energetic Atoms, Version 3	ASPERA-3	Southwest Research Institute	MO	Mars	Extended Science Operations
Dawn	Dawn	University of California Los Angeles	Full Mission	Asteroid	Science Operations

Mission Name	Mission Acronym	Principal Investigator Organization	Mission Type	Solar System Target	Mission Phase
Gravity Recovery and Interior Laboratory	GRAIL	Massachusetts Institute of Technology	Full Mission	Moon	Development
MErcury Surface, Space ENvironment, GEochemistry and Ranging	MESSENGER	Carnegie Institution of Washington	Full Mission	Mercury	Operations
Strofiio	Strofiio	Southwest Research Institute	MO	Mercury	Development

3.0 Background and Goals of the Workshop

The workshop was organized by the Discovery Program Executive (Lindley Johnson) and Discovery Program Scientist (Dr. Michael New), both located at NASA Headquarters. Science planning process education and sharing of lessons learned were the primary goals of the workshop.

The data sharing between Discovery missions was achieved through a series of informal briefings given by the mission Principal Investigators (PIs) accompanied by a question and answer session. Invited speakers were the PIs for missions that were currently in or relatively close to entering their formal spacecraft operational or science data gathering phases. These mission teams have developed and acquired valuable planning and operational knowledge that can be applied to Discovery missions that are early in their project life cycles. The intent of the workshop was to share this information primarily for the education of the other mission teams. Another indirect goal is risk reduction for future Discovery missions.

The invited mission speakers were asked to provide:

- Overview of the mission
- Overview of the Science Objectives
- Details of the Science planning, implementation data archival processes (including any unique software tools that are utilized or have been developed by the project)
- Lessons learned

4.0 Synopsis of Proceedings

As requested, the invited mission briefings included mission overviews, mission science objectives and related operations planning, relevant lessons learned, gleaned wisdom, and advice for both current and future Discovery missions. The agenda for the workshop is shown in Appendix 1. The workshop participants are shown in Appendix 2. The Planetary Science Division Director's briefing is shown in Appendix 3.

The NASA Planetary Science Division's Education and Public Outreach (EPO) Lead, Kristen Erickson, provided a walk-on briefing during the workshop. These charts are included as Appendix 4.

The invited mission briefings are shown in Appendices 5-8. MESSENGER, Stardust-NeXT, GRAIL, and Dawn provided formal presentations.

The LADEE, Aspera-3, Kepler, Genesis, Strofio, and M³ missions were also represented at the workshop and were provided opportunities to address the group with lessons learned and feedback to the Discovery Program Office during the open forum session. Most all of the missions addressed the group ad hoc and without the use of charts. Generally, the missions were in agreement with the level of mission oversight currently being provided by the Discovery Program Office. No program management changes were recommended by the mission representatives.

Appendix 1 Agenda

Discovery Science Workshop Agenda

December 1-2, 2010

Day 1 (December 1)

- 08:30-08:45 Introduction (HQ Planetary Science Division Director) (Dr. James Green)
- 08:45-10:45 MESSENGER Presentation/Open Discussion
- 10:45-11:00 Break
- 11:00-01:00 Stardust-NExT Presentation/Open Discussion
- 01:00-02:00 Lunch
- 02:00-02:15 Planetary Science Division EPO Presentation
- 02:15-04:00 GRAIL Presentation/Open Discussion
- 04:00-04:30 Open Discussion
- 04:30-05:30 Social Hour
- 06:00-08:00 Dinner

Day 2 (December 2)

- 08:30-08:45 Introduction
- 08:45-10:45 Dawn Presentation/Open Discussion
- 10:45-11:00 Break
- 11:00-12:00 Round Table Discussion/Adjourn

Appendix 2 Participants

The workshop participants are shown in Table A2-1.

Table A2-1 Workshop Participants

Last Name	First Name	Organization	e-mail address
A'Hearn	Mike	UMd	mahearn@mac.com
Anderson	Brian	JHU-APL	brian.anderson@jhuapl.edu
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Baggett	Randy	NASA MSFC	randy.m.baggett@nasa.gov
Bedini	Peter	JHU-APL	bedini@jhuapl.edu
Cahoy	Kerri	MIT	kerri.cahoy@gmail.com
Carro	Tony	NASA HQ	acarro@hq.nasa.gov
Clardy	Dennon	NASA MSFC	dennon.j.clardy@nasa.gov
Crane	Philippe	NASA HQ	pcrane@hq.nasa.gov
Elphic	Rick	NASA ARC	richard.c.elphic@nasa.gov
Frahm	Rudy	SwRI	rfrahm@swri.edu
Galloway	Paul	NASA MSFC/TBE	paul.n.galloway@nasa.gov
Gautier	Thomas	JPL	thomas.n.gautier@jpl.nasa.gov
Grammier	Rick	JPL	richard.s.grammier@jpl.nasa.gov
Grayzeck	Ed	NASA HQ	edwin.j.grayzeck@nasa.gov
Green	James	NASA HQ	james.green@nasa.gov
Hine	Butler	NASA ARC	butler.p.hine@nasa.gov
Hunter	Roger C.	NASA ARC	roger.c.hunter@nasa.gov
Johnson	Lindley	NASA HQ	lindley.johnson@nasa.gov
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Kelley	Michael	NASA HQ	michael.s.kelley@nasa.gov
Knopf	William	NASA HQ	wknopf@hq.nasa.gov
Larson	Tim	NASA HQ	tlarson@nasaprs.com
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Smith	David	MIT	smithde@mit.edu
Solomon	Sean	CIW	scs@dtm.ciw.edu
Sweetnam	Don	JPL	dsweetnam@charter.net
Turner	Rick	NASA MSFC	rick.turner@nasa.gov
Varanasi	Padma	JPL	padma.varanasi@jpl.nasa.gov
Washington	Monica	NRESS	mwashington@nasaprs.com
White	Mary	JPL	mary.l.white@jpl.nasa.gov
Zuber	Maria	MIT	mtz@mit.edu



Upcoming Planetary Science Mission Events (as of 11/22/10)



2010

- * September 16 – LRO transfer to SMD
- * November 4 - EPOXI encounters Comet Hartley 2
- * November 19 - Launch of O/OREOS
- December 7- Venus Climate Orbiter (JAXA) arrives at Venus

2011

- February 14 - Stardust NExT encounters comet Tempel 1
- Early March – Planetary Decadal Survey
- March 18 - MESSENGER orbit insertion at Mercury
- July - Dawn orbit insertion at asteroid Vesta
- August 5 - Juno launch to Jupiter
- September 8 - GRAIL launch to the Moon
- November 25 - MSL launch to Mars

2012

- Mid-year -- Mars Opportunity Rover gets to Endeavour Crater
- Mid-year -- Dawn leaves Vesta starts on its journey to Ceres
- August - MSL lands on Mars

* Completed

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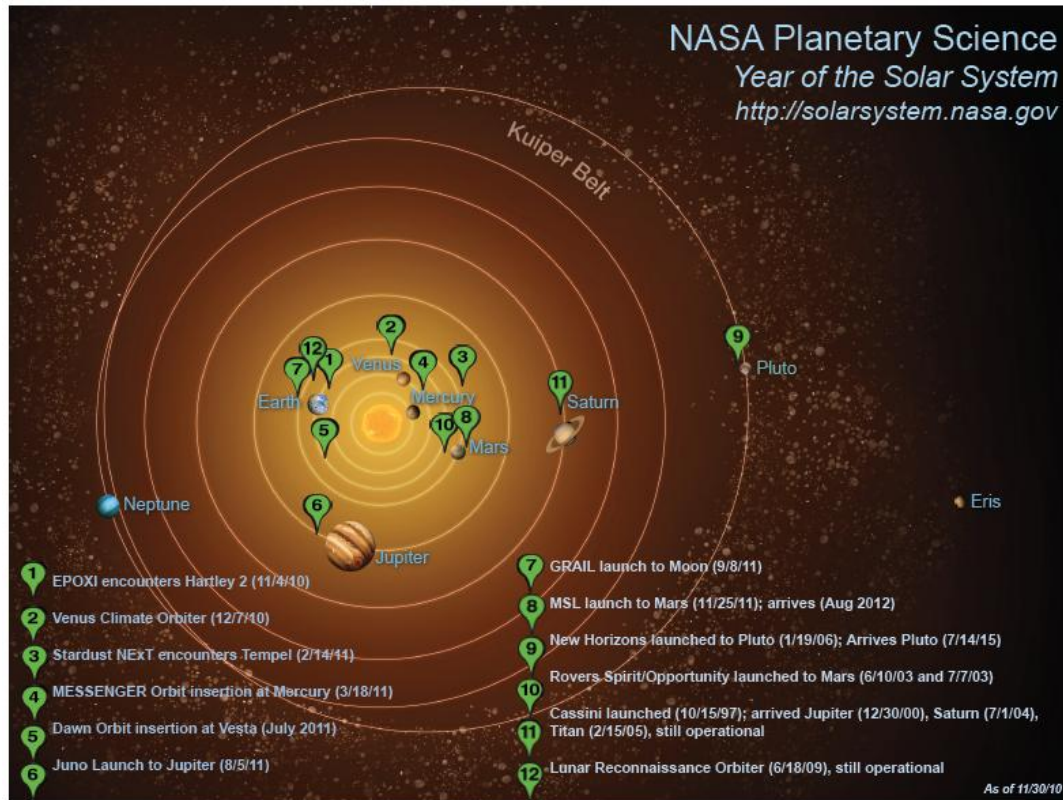
Happy Holidays From Planetary Science



2010



Appendix 4 HQ Planetary Science Division EPO Briefing (Kristen Erickson)



Year of the Solar System

"The Year of the Solar System presents a unique opportunity for NASA to raise awareness in a way that allows everyone to better understand our Solar System and consequently planet Earth." James L. Green, Director NASA Planetary Science

Purpose – PSD's Year of the Solar System (YSS) initiative is to raise awareness, build excitement and make connections with educators, students and the American public on planetary science activities. Approaches will be refined within the context of other NASA and Science Mission Directorate (SMD) Education and Public Outreach (E/PO) activities.

Theme: New Worlds, New Discoveries

Website: <http://solarsystem.nasa.gov>

Duration: October 2010 and continuing for one Martian year (687 Earth days) ending in late August 2012

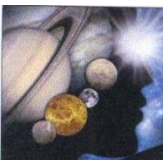
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Year of the Solar System Challenge

1. Come up with Three Reasons on why the general public should care about your mission
2. Relate back to here on Earth (visually, analogs, anecdotes)
3. Tie into upcoming events or missions to help raise awareness
4. Reference solarsystem.nasa.gov site

2



Year of the Solar System Contacts

Planetary Science Strategic Communications

<http://solarsystem.nasa.gov>

<http://solarsystem.nasa.gov/eyes>

Year of the Solar System EPO website

Wikipedia support

Kristen Erickson at
kristen.erickson@nasa.gov

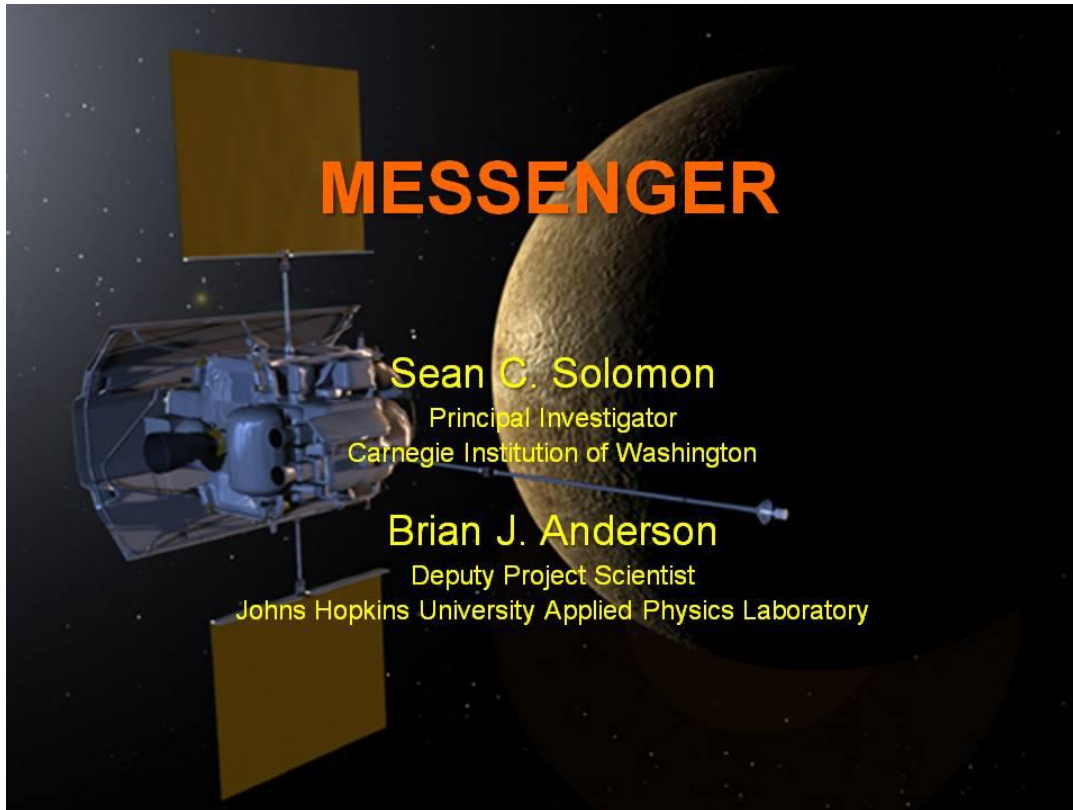
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Sean C. Solomon
Principal Investigator
Carnegie Institution of Washington

Brian J. Anderson
Deputy Project Scientist
Johns Hopkins University Applied Physics Laboratory



MESSENGER Outline



- Mission Overview
 - General background
 - Constraints associated with mission and spacecraft design
- Science Overview
 - Guiding science questions
 - Major mission objectives
 - Planned measurements required to meet objectives
- Science Planning
 - General approach
 - Building the baseline plan
 - The process
 - The planning tools
- Discussion



MESSENGER

Project Summary



The **M**ercury **S**urface, **S**pace **E**nvironment, **G**eochemistry, and **R**anging mission was selected in 1999 as NASA's 7th Discovery Program mission.

- The principal investigator institution is the Carnegie Institution of Washington.
- The Johns Hopkins University Applied Physics Laboratory (APL) is responsible for:
 - Spacecraft and instrument development
 - Mission operations
 - Project management
 - Science team participation
- The science instruments were developed by:
 - APL
 - The University of Michigan
 - The University of Colorado
 - NASA's Goddard Space Flight Center
- Launched on 3 August 2004, MESSENGER became the first spacecraft to encounter Mercury in over 30 years, and soon will become the first to orbit it.
- Orbit insertion on 18 March 2011 will initiate one Earth-year of orbital operations.

Participation Map (Gold States)

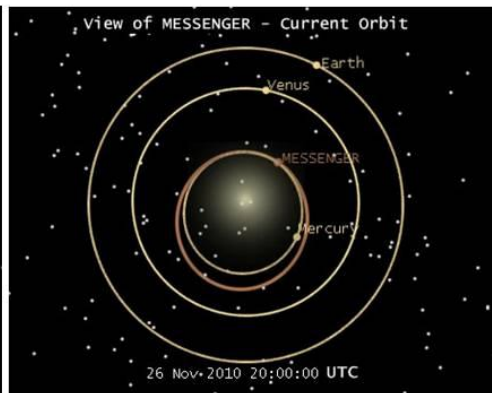
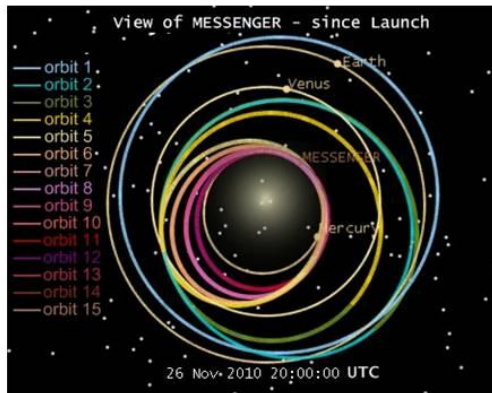
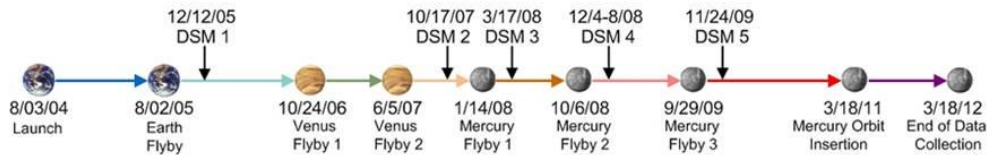


GOLD = Participant



MESSENGER

Mission Design



Achieving orbit about Mercury requires six planetary flybys, six propulsive maneuvers, 600 kg of propellant, and 6.6 years.

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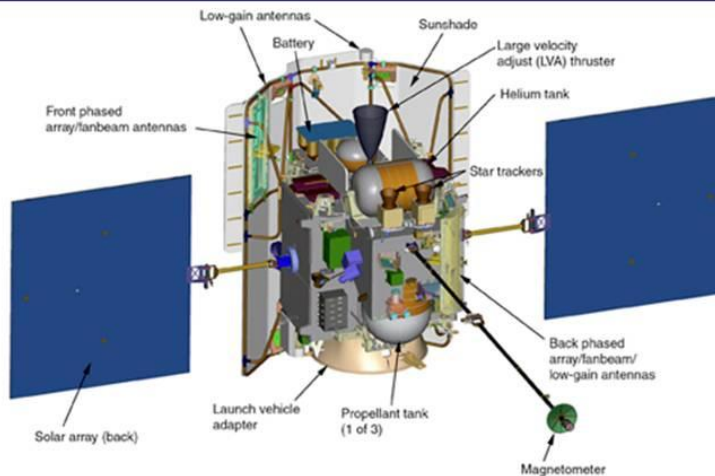


MESSENGER

Spacecraft Design Approach



- The long cruise duration demands a fully redundant spacecraft.
- More than half of the lift mass is propellant, leaving only ~ 500 kg for the spacecraft.
 - Subsystems and instruments were miniaturized as much as was feasible.



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MESSENGER

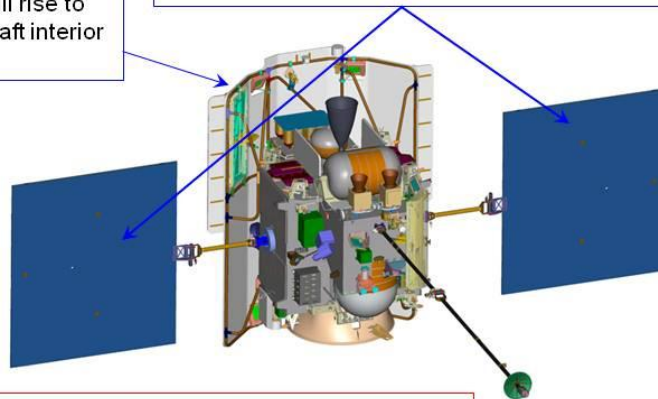
Thermal Protection



A ceramic-cloth sunshade shields the spacecraft interior to allow the use of essentially standard electronics, components, and blanketing materials.

The sunshade temperature will rise to over 300°C while the spacecraft interior is maintained at ~ 20°C.

The solar arrays operate reliably to ~ 150°C but would be at ~ 270°C at perihelion if left normal to the Sun.



The on-board autonomy system must maintain spacecraft pointing toward the Sun at all times.

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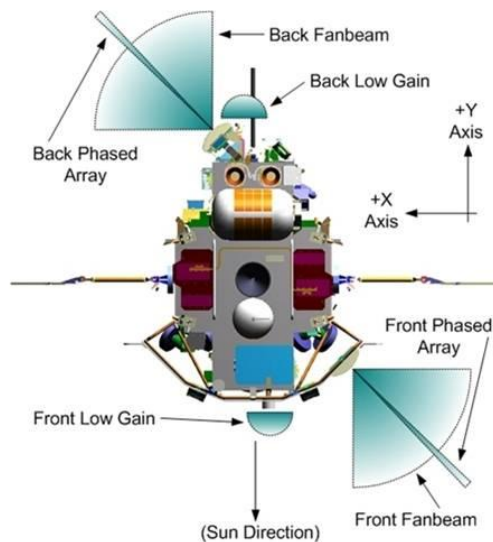


MESSENGER

Telecommunications



To avoid operating (and qualifying) a gimbaled antenna system at temperatures in excess of 300°C, a steerable phased-array system was developed.



- Two arrays of eight slotted waveguide "sticks" are driven by separate amplifier channels.
- Electronic steering in one dimension over a range of $\pm 45^\circ$ is accomplished by controlling the relative phases of the eight amplifier channels.



The spacecraft must be placed into downlink attitude to send data to Earth.

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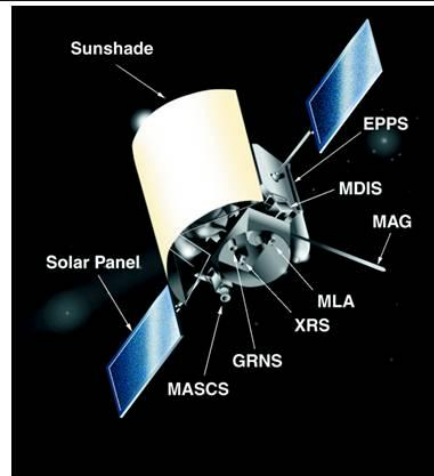


MESSENGER



Payload

- Mercury Dual Imaging System (MDIS)
- Gamma-Ray and Neutron Spectrometer (GRNS)
- X-Ray Spectrometer (XRS)
- Magnetometer (MAG)
- Mercury Laser Altimeter (MLA)
- Mercury Atmospheric and Surface Composition Spectrometer (MASCS)
- Energetic Particle and Plasma Spectrometer (EPPS)
- Radio Science (RS)



Instruments that point share the +Z boresight.

MDIS is the only instrument that articulates; all others are fix-mounted.

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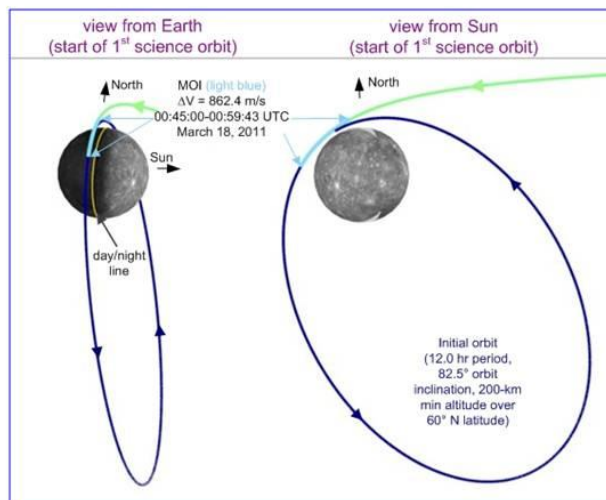
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MESSENGER



Orbit Design



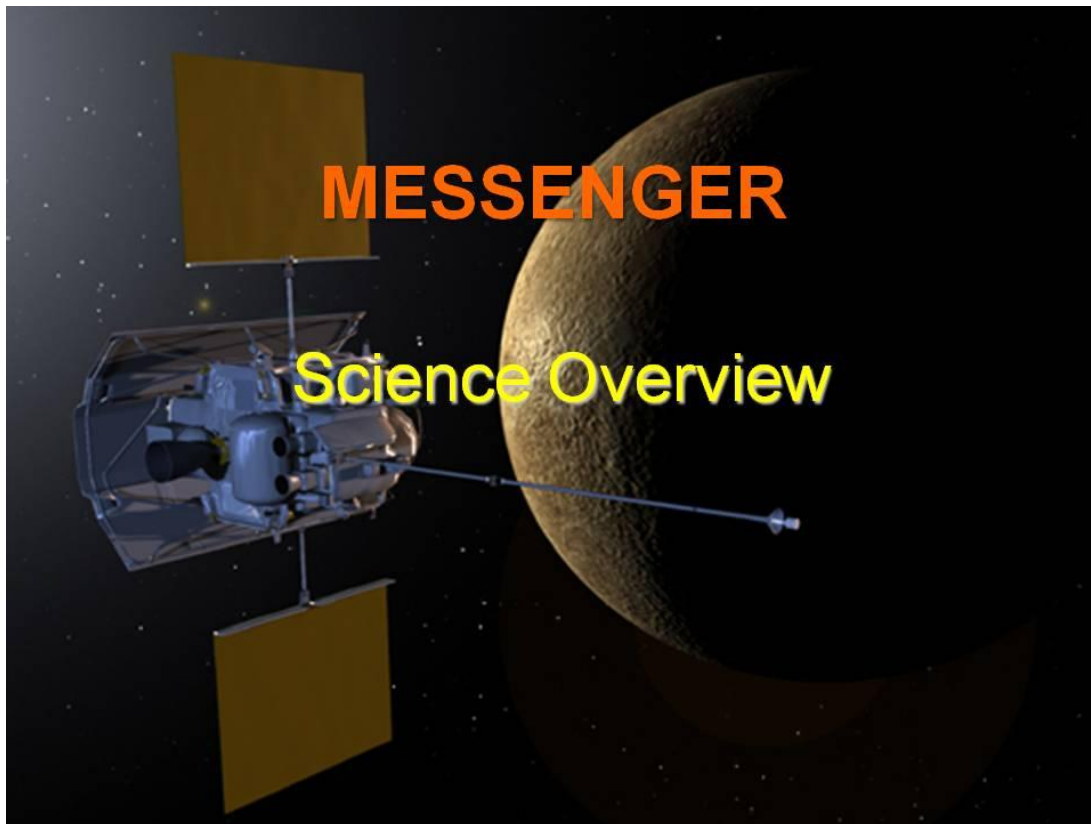
A highly elliptical orbit is needed to keep the spacecraft from getting too hot.

Because of Mercury's 3:2 spin-orbit resonance, one Earth year equals two Mercury solar days.

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MESSENGER



Six Science Questions Frame the Mission



- Why is Mercury so dense?
- What is the geological history of Mercury?
- What is the nature of Mercury's magnetic field?
- What is the structure of Mercury's core?
- What are the unusual materials at Mercury's poles?
- What volatiles are important at Mercury?



MESSENGER

Science Objectives



In order to address the six science questions, MESSENGER has six primary science objectives:



- Determine the chemical composition of Mercury's surface.
- Determine Mercury's geological history.
- Determine the geometry of the planet's magnetic field.
- Determine the size and state of Mercury's core.
- Determine the volatile inventory at Mercury's poles.
- Determine the nature of Mercury's exosphere and magnetosphere.

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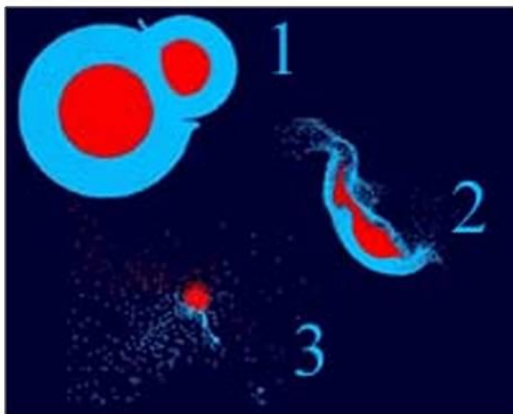
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Mercury's Bulk Composition



University of Bern/Horner et al., 2006

- What planetary formational processes led to the high metal/silicate ratio in Mercury?
- At what solar distance did Mercury form?
- Was the high metal/silicate ratio imparted early or late in the growth sequence?
- Elemental chemistry of surface can distinguish among possible hypotheses.
- X-ray, γ -ray, and neutron spectrometry can measure or bound the abundances of key elements, e.g., Mg, Al, Si, Ca, Ti, and Fe.

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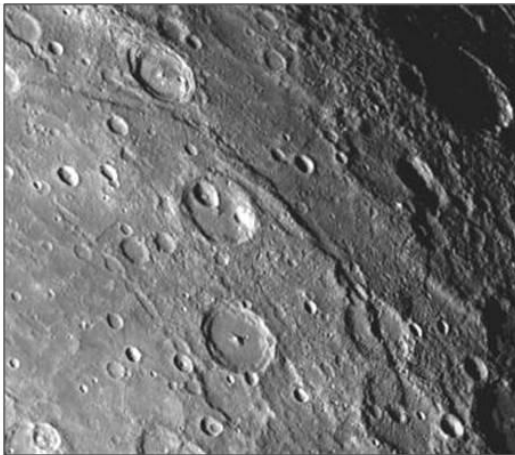
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MESSENGER



Mercury's Geological History



- Can differences in geological history among the terrestrial planets be related to planet size or initial conditions?
- How important has volcanism been in Mercury's history?
- Will aspects of Mercury's geological evolution (e.g., ancient cessation of magmatic activity, global contraction) require substantial revision?
- Global color imaging can address these issues.

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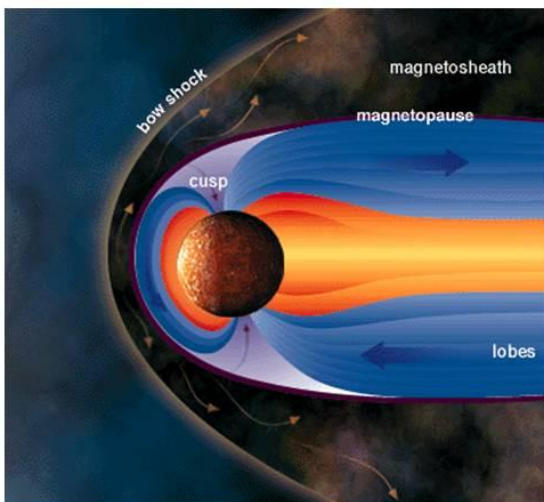
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MESSENGER



Mercury's Magnetic Field



www.windows.ucar.edu

- Mercury's magnetosphere provides an important comparison to that of Earth.
- Even dipole term not well-resolved by Mariner 10 data.
- Competing hypotheses for the internal field (remanence, hydromagnetic dynamo, thermoelectric currents) predict different field geometries.
- Internal field can be separated from external field by repeated orbital magnetometer measurements.

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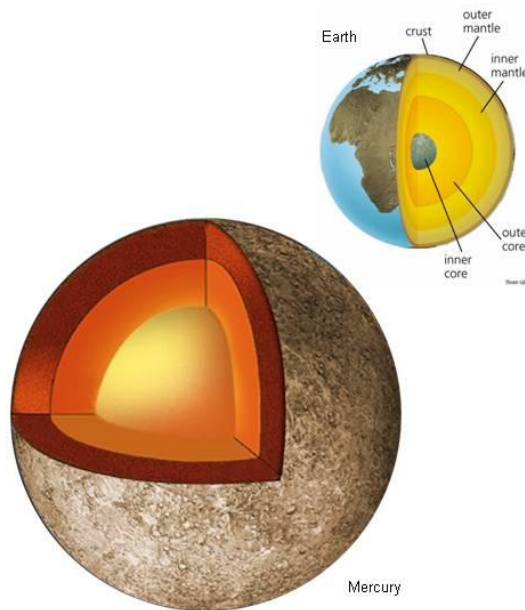


MESSENGER

Mercury's Core



- Core radius ~ 75% of planet radius (from bulk density).
- Presence and thickness of a fluid outer core depends on the concentration of light alloying elements.
- Amplitude of forced libration for a solid planet and one with a liquid outer core differ by a factor of 2.
- Ascertain libration by determining departures from uniform spin with laser altimetry.
- Determine moments of inertia by measuring C_{20} and C_{22} from spacecraft tracking.



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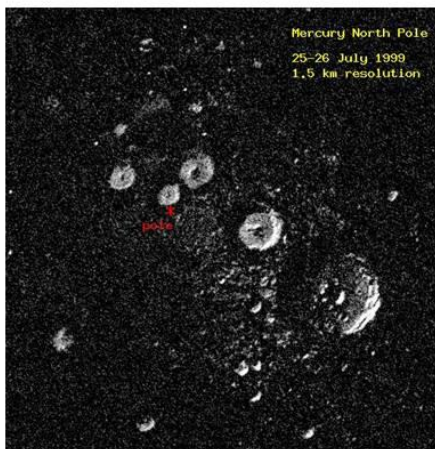
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Mercury's Polar Deposits



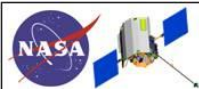
Arecibo radar image of north polar deposits [Harmon *et al.*, 2001].

- Radar-bright deposits are seen within permanently shadowed regions near Mercury's poles.
- Cold trapping of water ice on the floors of permanently shadowed craters is the leading explanation.
- Chemical remote sensing and altimetry can distinguish among alternatives.
 - Gamma-ray and neutron spectrometry of polar regions can detect O, H, S.
 - UV spectrometry of the polar atmosphere can detect H and O and search for S and OH.
 - Altimetry of polar craters can test the cold-trap hypothesis.

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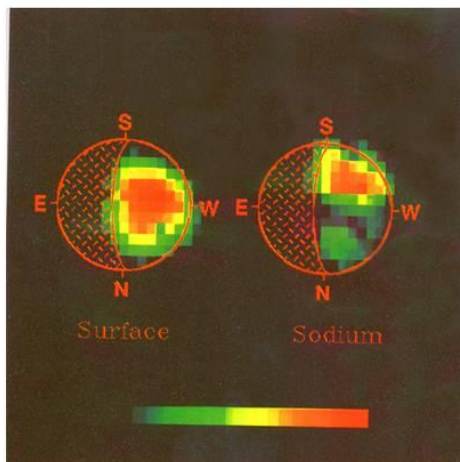
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Mercury's Volatile Budget



Na emission, Mercury atmosphere
[Potter and Morgan, 1997].

- Charged-particle measurements can be diagnostic of sources and loss mechanisms.
- UV spectrometry can measure profiles of known (H, O, Na, K, Ca, Mg) and expected (e.g., Si, Al, Fe, S, OH) species.
- Energetic-particle and plasma measurements can determine the composition, distribution, and energy of charged particles in Mercury's magnetosphere.
- Measurement of temporal and spatial variability is necessary.

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MESSENGER

Measurement Objectives



Each of the six guiding science questions that frame the mission will be answered by observations from two or more instruments, and the observations from each instrument will address more than one question.

Guiding Science Question	Mission Objective	Measurement Objective
Why is Mercury so dense?	Determine the chemical and mineralogical composition of Mercury's surface.	Surface element abundances: GRNS and XRS Spectral measurements of surface: MASCS (VIRS)
What is the geologic history of Mercury?	Determine Mercury's geologic history via multi-spectral/stereo imaging and topography.	Global imaging in color: MDIS (WAC) Targeted high-resolution imaging: MDIS (NAC) Global stereo imaging: MDIS Spectral measurements of geological units: MASCS (VIRS) Northern hemisphere topography: MLA
What is the nature of Mercury's magnetic field?	Determine the nature of Mercury's magnetic field.	Mapping of internal magnetic field: MAG Magnetospheric structure: MAG, EPPS
What is the structure of Mercury's core?	Determine the size and state of Mercury's core via gravity field mapping and topography.	Gravity field, global topography, obliquity, libration amplitude: MLA, RS
What are the unusual materials at Mercury's poles?	Determine the volatile inventory at Mercury's poles by identifying material of polar deposits.	Composition of polar deposits: GRNS Polar exosphere: MASCS (UVVS) Polar ionized species: EPPS Altimetry of polar craters: MLA
What volatiles are important at Mercury?	Determine the nature of Mercury's exosphere and magnetosphere.	Neutral species in exosphere: MASCS (UVVS) Ionized species in magnetosphere: EPPS Solar wind pick-up ions: EPPS Elemental abundances of surface sources: GRNS, XRS

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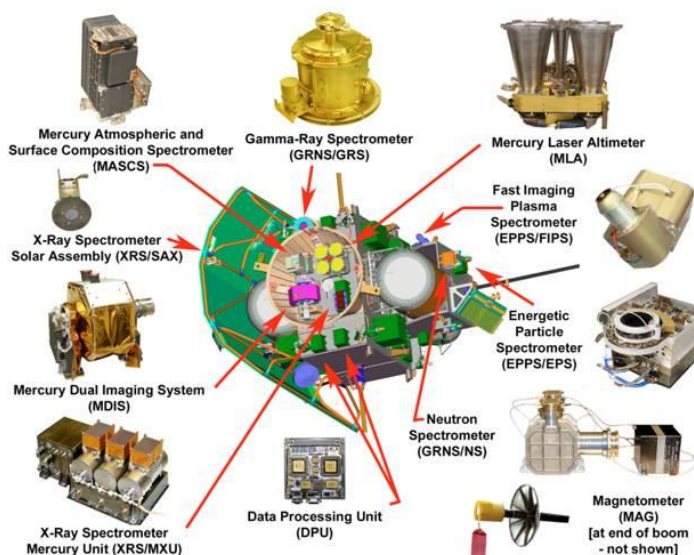
MESSENGER



Science Payload (7 Instruments + Radio Science)

- **MESSENGER** payload mass is 47.2 kg, including mounting hardware, thermal control components, purge system, payload harnesses, and magnetic shielding for the spacecraft reaction wheels. The mass for MDIS includes the calibration target. The MAG mass includes a 3.6-m boom.

- Nominal average power consumption per orbit is 84.4 W; actual values will vary with instrument operational mode and spacecraft position in orbit.



Instrument details can be found at <http://messenger.jhuapl.edu/instruments/index.html>

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MESSENGER

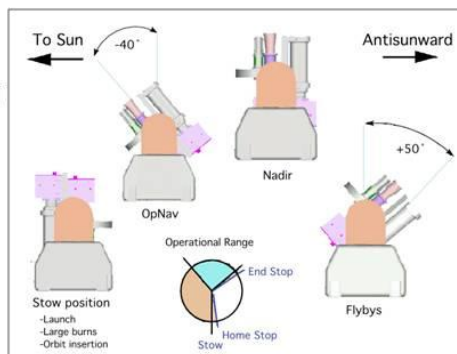
Mercury Dual Imaging System (MDIS)



- Two imagers with pivot platform
 - Wide-angle (10.5° FOV) camera (WAC)
 - Narrow-angle (1.5° FOV) camera (NAC)
- Will carry out a comprehensive mapping survey of the surface by
 - Imaging landforms
 - Mapping variations in surface color and texture
 - Mapping topography with stereo imaging



- **Mass:** 8.0 kg
- **Power:** 7.6 W
- **Development:** APL



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MESSENGER Gamma-Ray and Neutron Spectrometer (GRNS)

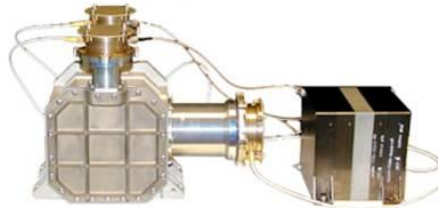


- Spectrometers detect gamma rays and neutrons emitted by
 - Radioactive elements on Mercury's surface
 - Surface elements stimulated by cosmic rays
- Will be used to map the relative abundances of different elements (e.g., O, Si, S, Fe, H, K, U, Th)
- Will help to determine if water ice exists at Mercury's poles

- **Mass:** 9.2 kg
- **Power:** 16.5 W
- **Development:** APL, Patriot Engineering, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory



Gamma-Ray Spectrometer



Neutron Spectrometer

- **Mass:** 3.9 kg
- **Power:** 6.0 W
- **Development:** APL, Patriot Engineering, Los Alamos National Laboratory

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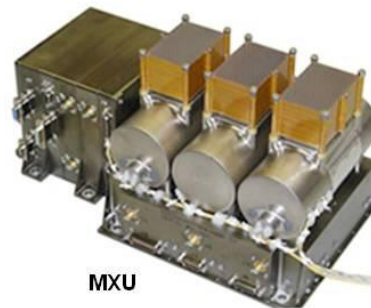


MESSENGER X-Ray Spectrometer (XRS)



- Two detectors:
 - Mercury X-Ray Unit (MXU) pointing at the planet
 - Solar Assembly for X-rays (SAX), pointing at the Sun
- High-energy solar X-rays that strike Mercury cause surface elements to emit X-rays at diagnostic energies
- XRS detects these emitted X-rays and determines ratio of solar incident X-rays to those emitted by Mercury
- Measures the abundance of various elements, e.g., Mg, Al, Si, Ca, Ti, and Fe

SAX



MXU

- **Mass:** 3.4 kg
- **Power:** 6.9 W
- **Development:** APL

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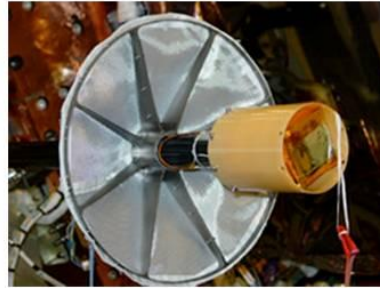


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Magnetometer (MAG)



- Three-axis, ring-core fluxgate detector
- MAG sensor is mounted on a 3.6-m boom to keep it away from the spacecraft's own magnetic field
- Can collect magnetic field samples at 50-ms to 1-s intervals
- MAG measures the strength and orientation of Mercury's magnetic field and will search for magnetized portions of the planet's crust



- **Mass:** (including boom): 4.4 kg
- **Power:** 4.2 W
- **Development:** NASA Goddard Space Flight Center and APL

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Mercury Laser Altimeter (MLA)



- Measures topography of northern hemisphere to meter precision (MDIS stereo and limb imaging and occultations cover southern hemisphere)
- Used to measure amplitude of forced libration
- Provides a detailed surface-height profile to better than 30 cm relative precision
- Has 1800 km range and precision to < 0.5 m
- Radio tracking measures gravity, and the combination of gravity and topography constrains the thickness of Mercury's lithosphere and crust



- **Mass:** 7.4 kg
- **Power:** 16.4 W
- **Development:** NASA Goddard Space Flight Center

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Mercury Atmospheric and Surface Composition Spectrometer (MASCS)



- Spectrometer is sensitive to light from the infrared to the ultraviolet
 - Visible and Infrared Spectrograph (VIRS), 300-1450 nm
 - Ultraviolet and Visible Spectrometer (UVVS), 115-600 nm
- Will measure the abundances of atmospheric species in Mercury's exosphere and tail and map mineralogical absorption features in surface materials
- Will compare surface measurements with those from MDIS

- **Mass:** 3.1 kg
- **Power:** 6.7 W
- **Development:** Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder



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Energetic Particle and Plasma Spectrometer (EPPS)



- Two instruments measure the composition, distribution, and energy of charged particles in Mercury's magnetosphere.
- Fast Imaging Plasma Spectrometer (FIPS) measures thermal plasma.
 - Can detect H, He, O, Na, K, S, Ar, Fe
- Energetic Particle Spectrometer (EPS) measures energetic ions and electrons.
 - Can detect H, He, Fe, and electrons

- **Mass:** 3.1 kg
- **Power:** 7.8 W
- **Development:** APL and University of Michigan

EPS



FIPS



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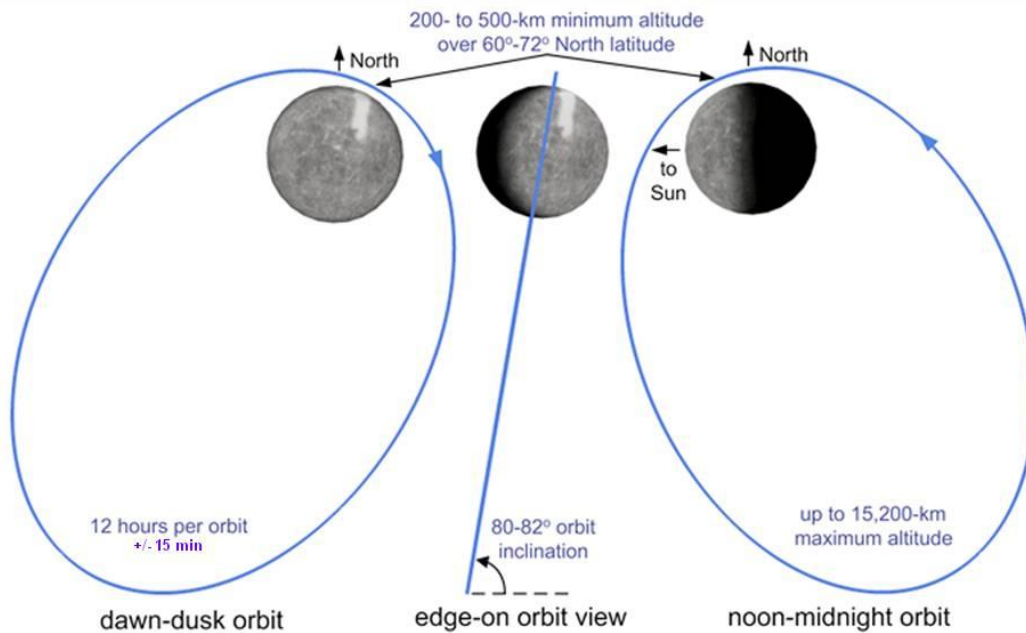
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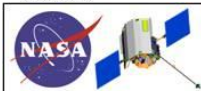
Working from Orbit



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Why This Orbit?

The orbit around Mercury followed by the MESSENGER spacecraft must meet engineering requirements (such as pointing the sunshade toward the Sun) while facilitating the measurements of all elements of the science investigation.

Science Question	Mission Design Requirement	Mission Design Feature
Globally image surface @ 250-m resolution	Provide two solar days at two geometries for stereo image of entire surface; near-polar orbit for full coverage (MDIS)	Orbital phase duration chosen at one Earth year with periapsis altitude controlled to 200-500 km, 82.5° inclination orbit
Determine structure of magnetic field	Minimize periapsis altitude; maximize altitude-range coverage (MAG)	Periapsis altitude from 200-500 km; Apoapsis altitude near 15,200 km for 12-hour orbital period (+/- 10 minutes)
Map elemental and mineralogical composition of surface	Maximize time at low altitudes (GRNS, XRS)	
Measure libration amplitude and gravitational field structure	Minimize orbital-phase thrusting events (RS, MLA)	Initial orbital inclination 82.5°; periapsis latitude drifts from 60° N to 68° N; primarily passive momentum management; orbit corrections every 88 days
	Orbital inclination <85°; latitude of periapsis near 60° N (MLA, RS)	
Determine composition of radar-reflective materials at poles	Initial orbital inclination 82.5°; latitude of periapsis maintained near 60° N (GRNS, MLA, MASCS, EPPS)	
Characterize exosphere neutrals and accelerated magnetosphere ions	Wide altitude-range coverage; visibility of atmosphere at all lighting conditions	Extensive coverage of magnetosphere; Orbit cuts bow shock, magnetopause, and upstream solar wind

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Program Level-1 Requirements

4.1.2 Full Mission Success Criteria

Full success for the MESSENGER mission shall be achieved by (i) inserting the spacecraft into an elliptical, near-polar orbit about Mercury, (ii) carrying out a global survey of the planet for one Earth year, and (iii) accomplishing the following six tasks:

- (1) Provide major-element maps of Mercury to 10% relative uncertainty on the 1000-km scale and determine local composition and mineralogy at the ~20-km scale.
- (2) (a) Provide a global map with > 90% coverage (monochrome) at 250-m average resolution and > 80% of the planet imaged stereoscopically, (b) provide a global multi-spectral map at 2 km/pixel average resolution, and (c) sample half of the northern hemisphere for topography at 1.5-m average height resolution.
- (3) Provide a multipole magnetic-field model resolved through quadrupole terms with an uncertainty of less than ~20% in the dipole magnitude and direction.
- (4) Provide a global gravity field to degree and order 16 and determine the ratio of the solid-planet moment of inertia to the total moment of inertia to ~20% or better.
- (5) Identify the principal component of the radar-reflective material at Mercury's north pole.
- (6) Provide altitude profiles at 25-km resolution of the major neutral exospheric species and characterize the major ion-species energy distributions as functions of local time, Mercury heliocentric distance, and solar activity.

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Program Level-1 Requirements

4.1.3 Minimum Mission Success Criteria

Minimum success for the MESSENGER mission shall be achieved by (i) inserting the spacecraft into orbit about Mercury, (ii) acquiring globally distributed science data from the Mercury flybys and 90 Earth days in Mercury orbit, and (iii) accomplishing three out of the following five tasks:

- (1) Determine surface elemental composition, including one pole, to 10% relative uncertainty.
- (2) Provide global maps of the planet in monochrome at 500 m/pixel and in color at 2 km/pixel.
- (3) Determine the intrinsic planetary magnetic field strength and configuration.
- (4) Provide altimetry and gravity field structure of the northern hemisphere.
- (5) Distinguish a liquid from a solid core.

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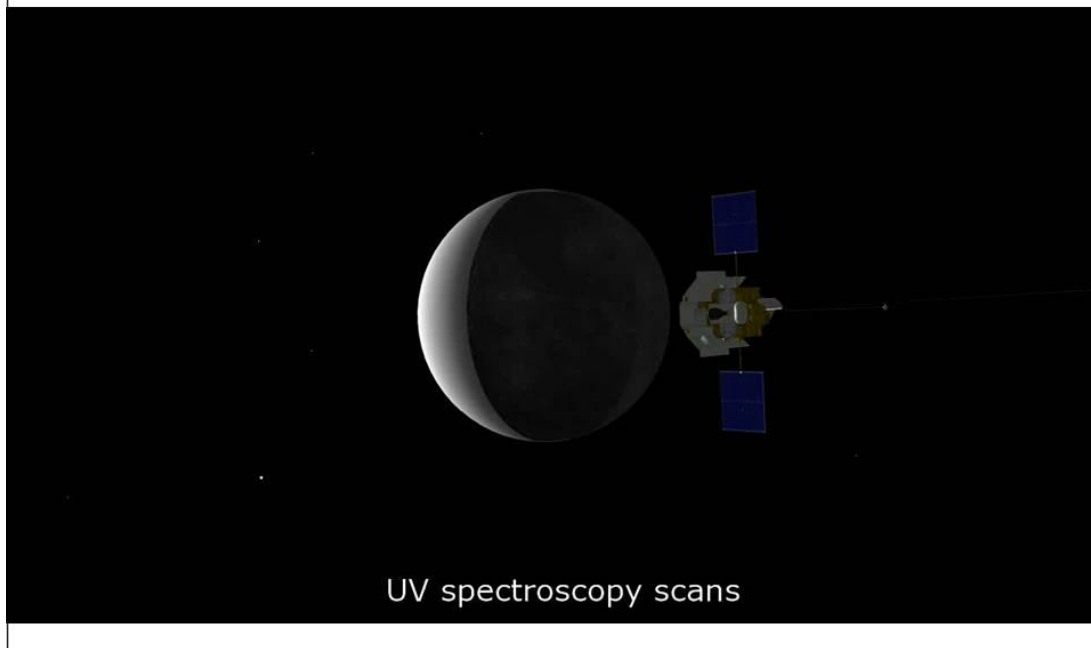
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M2 Flyby: = 1/720th or Orbital Mission



UV spectroscopy scans



MESSENGER

The Science Planning Challenge



- Observing constraints:
 - One Earth year of operations means two (Mercury solar) days to complete the observations
 - Spacecraft sunshade must face the Sun at all times
 - Highly elliptical orbit extends from 200 km to more than 15,000 km altitudes
 - Only MDIS moves, and only in one direction
 - Spacecraft must turn for targeted observations and to downlink data
- Observing objectives (from program level requirements):
 - Provide major-element maps of Mercury to 10% relative uncertainty on the 1000-km scale and determine local composition and mineralogy at the ~20-km scale.
 - Provide a global map with > 90% coverage (monochrome) at 250-m average resolution and > 80% of the planet imaged stereoscopically. Also provide a global multi-spectral map at 2 km/pixel average resolution, and (c) sample half of the northern hemisphere for topography at 1.5-m average height resolution.
 - Provide a multi-pole magnetic-field model resolved through quadrupole terms with an uncertainty of less than ~20% in the dipole magnitude and direction.
 - Provide a global gravity field to degree and order 16 and determine the ratio of the solid-planet moment of inertia to the total moment of inertia to ~20% or better.
 - Identify the principal component of the radar-reflective material at Mercury's north pole
 - Provide altitude profiles at 25-km resolution of the major neutral exospheric species and characterize the major ion-species energy distributions as functions of local time, Mercury heliocentric distance, and solar activity

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General Approach



- The demands of the measurement objectives, coupled with the constraints associated with spacecraft safety and the orbital geometry led to the adoption of the following approach:
 - Plan the entire year of observations in advance of the orbital phase.
 - Develop the capability to re-generate the plan in short order in response to anomalies in flight (e.g., spacecraft safe mode demotion) or on the ground (e.g., missed DSN tracks).
- The SciBox tool has been developed along with the baseline plan.
- A process has been developed to address minor plan adjustments and major plan regenerations.

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SciBox Purpose



- **Science Observations Scheduling and Commanding**
- **Develop the MESSENGER orbit-phase observing plan**
 - Meet needs of each investigation
 - Stay within operational and hardware constraints
 - Provide reports on the details of the plan and tools to assess the plan
 - Heritage includes MRO CRISM investigation
 - Full mission simulations
 - Trajectory: from Mission Design
 - Instrument observation plans: based on ST concepts of operations
 - Spacecraft and operation constraints: from MSE and MOPs
- **Operational Support: Construct science command sequences**
 - Produce the commands sequence
 - Provide observation margin measures
 - Rapid re-planning/re-scheduling

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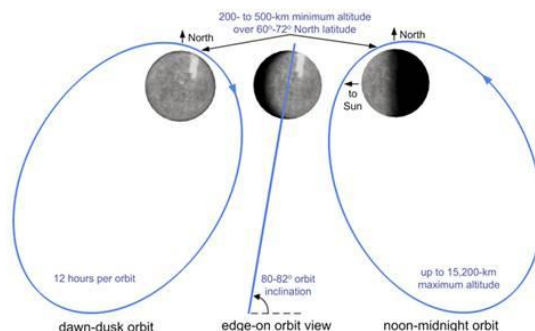


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Mercury & MESSENGER Orbits



- Mercury: 88-day orbit, 3:2 spin orbit resonance
 - 176 day 'solar-day' (3 spins = 2 orbits)
 - Imaging coverage with only two 'days' to work with
- Prioritize coverage by solar day (MDIS):
 - 1st day: Monochrome map and color
 - 2nd day: Stereo and monochrome/color recovery



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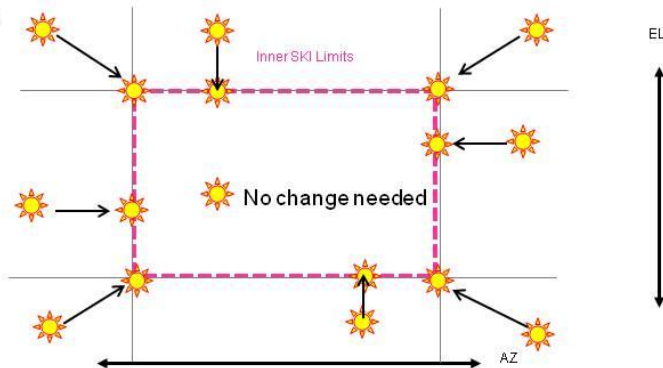


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Sun-Keep-In (SKI) Constraints

- SKI inner limits:
 - Elevation: ± 12 deg wrt Sun-centered
 - Azimuth: ± 10 deg wrt Sun-centered
- Slew rates:
 - Worst-case fixed slew rate assumption
 - < 0.015 r/s



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Instrument Science and Pointing

- MDIS is only instrument with coverage control, i.e. coverage is monitored and recovered if required.
- Targets involve sub-set of bore-sighted payload
- Re-scheduling 'missed' observations applies only to MDIS and Targets

Instrument	Science	Pointed	Coverage control	Targeting
EPPS	Magnetosphere	N	N	N
GRS	Composition	Y (bore-sight: broad FOV)	N	N
MAG	Magnetic field, magnetosphere	N	N	N
MDIS	Imaging: geology, mineralogy, topography	Y (roll & gimbal)	Y	Y
MLA	Ranging: planetary shape, rotation	Y (bore-sight)	N	Y
NS	Composition/volatiles	N (SC velocity, orientation dependent)	N	N
RS	Gravity field, shape	N (LOS doppler)	N	N
UVVS	Exosphere (mineralogy)	Y (bore-sight)	N	Y
VIRS	Mineralogy	Y (bore-sight)	N	Y
XRS	Composition	Y (bore-sight: broad FOV)	N	N

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Building the Baseline Plan/SciBox Development

- Directed by Project Science: Interface between science teams/discipline groups and software development and engineering teams
- Iterative SciBox/Baseline builds
 - Early development: Baseline Versions 0,1,2,3; Impose project approval: Change Control Board Versions 1, 2, 3, 4, 5.
 - Ingest predict trajectory for entire orbit year and generate complete year observation plan
 - Comprehensive reporting: instrument state, image table, observation coverage maps, MOPS-ready command requests (sasf files).
- Science team evaluation & iteration:
 - Instrument/discipline group concepts of operations: developed in concert with project science and engineering team
 - Direct interaction with software developers
 - Informal and formal instrument/discipline group reviews
 - Science team meetings: discipline group discussion forums & plenary trade analysis presentation and discussions
 - Formal orbit readiness reviews

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Science Prioritization

- Because of the rather heavy pointing constraints it was decided to prioritize observations based on which has control of spacecraft pointing.
 - MDIS makes extensive use of its pivot to optimize observations when it does not control the pointing.
 - MLA drives when the spacecraft is close to the planet (under ~1500 km altitude).
 - XRS drives when above 1500 km altitude and +Z axis on planet within SKI.
 - GRS drives when below 5000 km altitude if +Z axis is not on planet within SKI
 - UVVS drives when no other instruments can see the planet.
 - NS, EPPS, and MAG are ride-along instruments.
 - Downlink tracks have been optimized for RS measurements.
- Operations priorities:
 - Operations team to conduct the mission: Orbit Insertion, Orbit Corrections, Downlink, Momentum Dumps implemented via commanding and G&C exclusion windows
 - Mission science comes next: prioritized by PLR.
 - Science of opportunity comes last: margin against PLR.

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Scheduling Priority: 'Keys to the car'



1st Solar Day	2nd Solar Day
Eclipse	Eclipse
Orbit Correction Maneuver	Orbit Correction Maneuver
Mercury Orbit Insertion	G&C High Rate
G&C High Rate	Downlink - High Gain Antenna
Downlink - High Gain Antenna	Priority-1 Targets & VIRS phot 1
Post MOI	UVVS Polar Exosphere Scan
Priority-1 Targets & VIRS phot 1	MDIS Stereo Mapping
UVVS Polar Exosphere Scan	MLA North Polar Off-Nadir Coverage
MLA Northern Hemisphere Nadir Coverage	MLA Northern Hemisphere Nadir Coverage
Priority-2 Targets & VIRS phot 2	Priority-2 Targets & VIRS phot 2
MDIS-WAC South Pole Monitoring	MDIS NAC 3x2 South
UVVS Star Calibration	UVVS Star Calibration
XRS Star Calibration	XRS Star Calibration
MDS Limb Scan/Pivot Cal	MDS Limb Scan/Pivot Cal
UVVS Limb Scan	UVVS Limb Scan
Priority-3 Targets & VIRS phot 3	Priority-3 Targets & VIRS phot 3
XRS/VIRS Global Mapping	XRS/VIRS Mapping
MDIS Global Color Mapping	Priority-4 Targets & VIRS phot 4
MDIS Global Monochrome Mapping	UVVS Exosphere Scan
Priority-4 Targets & VIRS phot 4	MDIS North Polar Ride-Along
UVVS Exosphere Scan	MAG Observation
MAG Observation	GRS Northern Hemisphere Coverage
GRS Northern Hemisphere Coverage	NS Northern Hemisphere Coverage
NS Northern Hemisphere Coverage	EPS Observation
EPS Observation	FIPS Observation
FIPS Observation	RS - Low Gain Antenna
RS - Low Gain Antenna	Priority-5 Ride-Along Targeted Observations
Priority-5 Ride-Along Targeted Observations	Priority-6 Ride-Along Targeted Observations
Priority-6 Ride-Along Targeted Observations	Priority-7 Ride-Along Targeted Observations
Priority-7 Ride-Along Targeted Observations	

Key: G&C Commanding Required
No G&C commanding
Pivot commanding only

- Basic priority order
 - Operations
 - Top-level science
 - Opportunity science
- Altitude ordered initial science pointing priority
 - MLA below 1500 km
 - XRS: above 1500 km with planet in view on +Z
 - MDIS: above 1500 km, planet in view with pivot
 - MASCS: otherwise
- Detailed priority by solar day
 - First solar day: monochrome image mapping
 - Second solar day: gap coverage, targeted observations, specific campaigns

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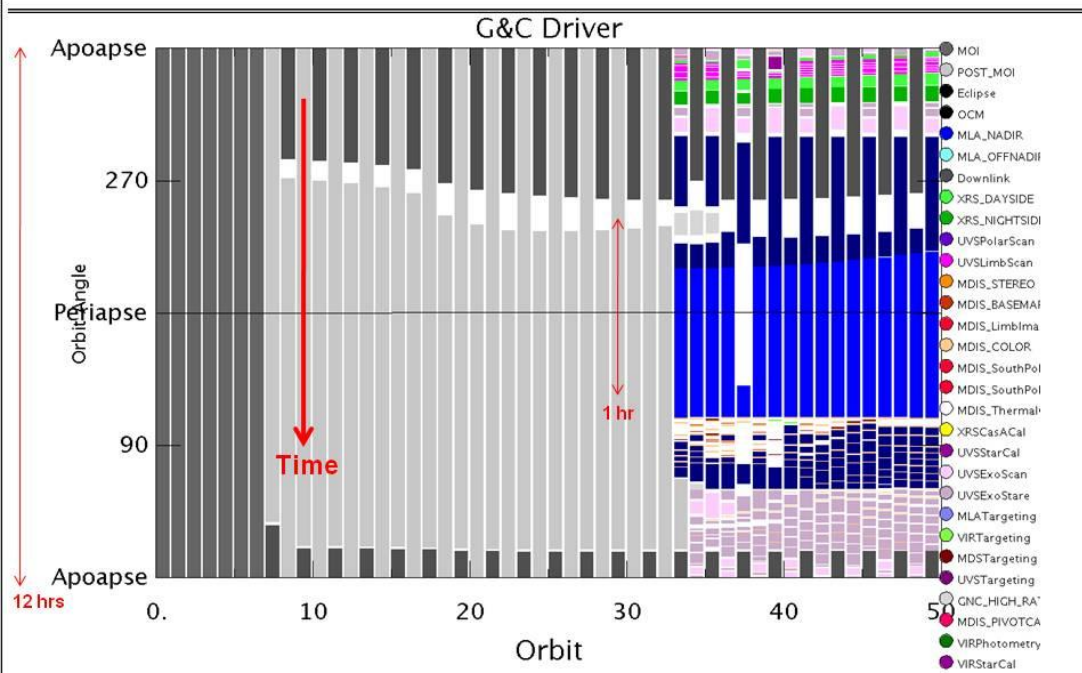
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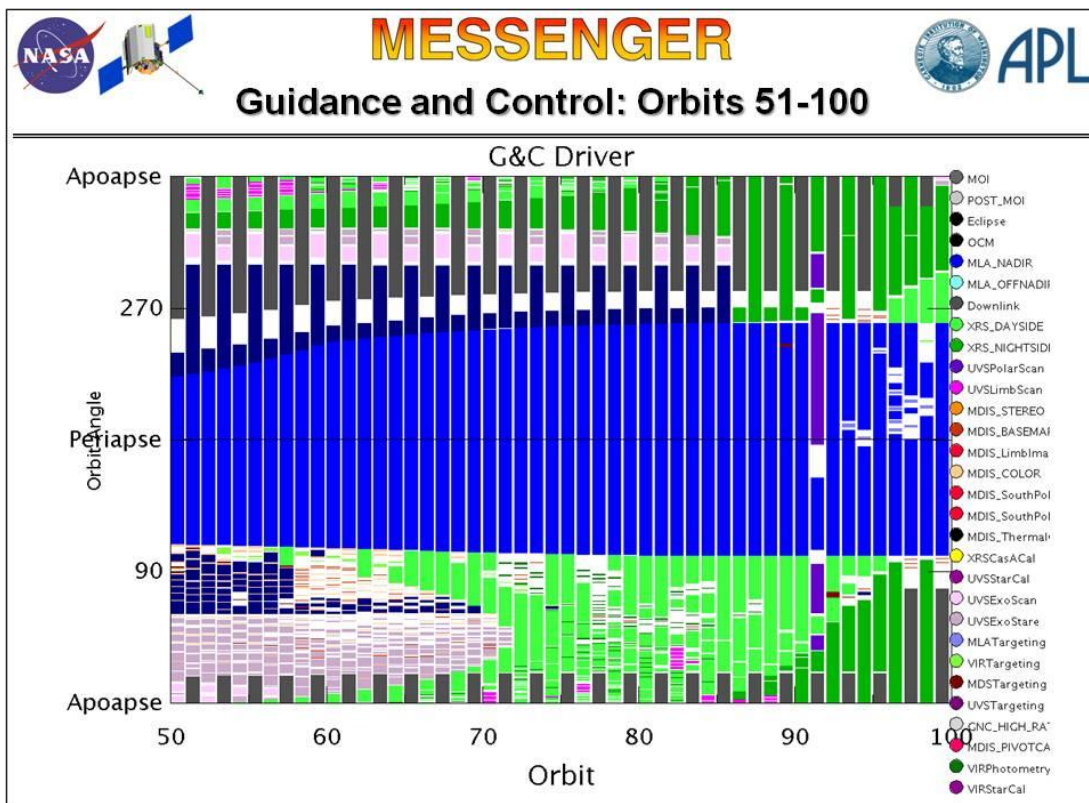
Guidance and Control first 50 orbits



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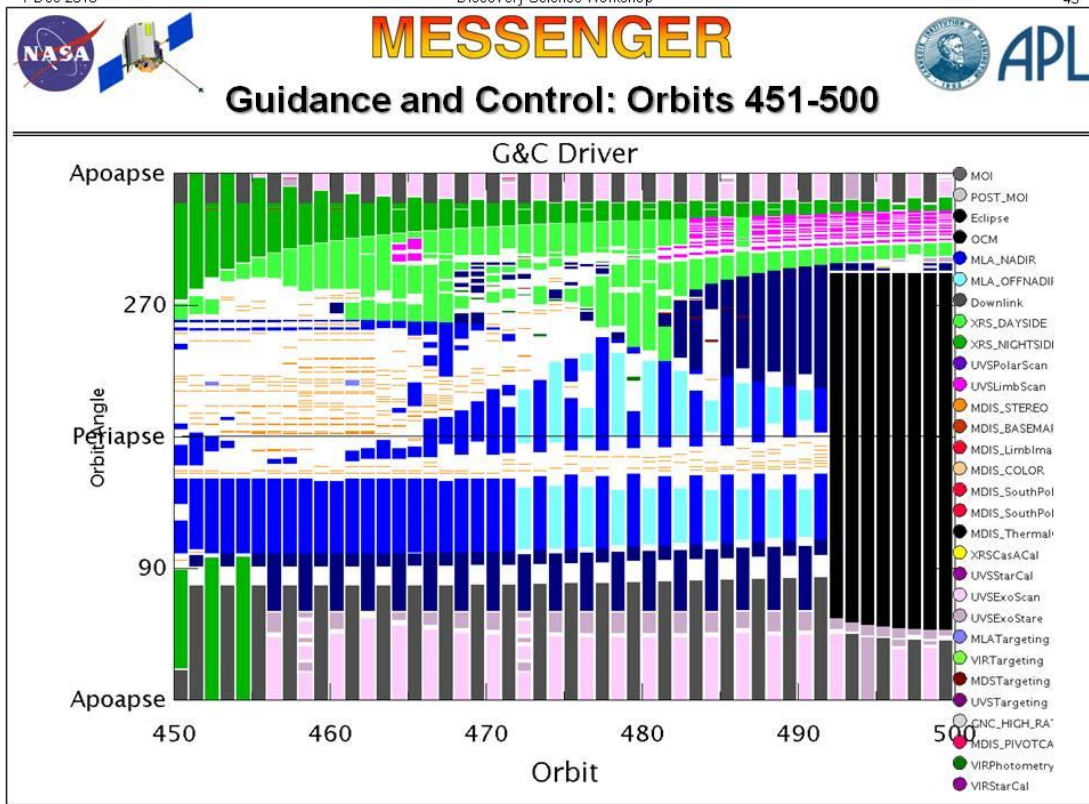
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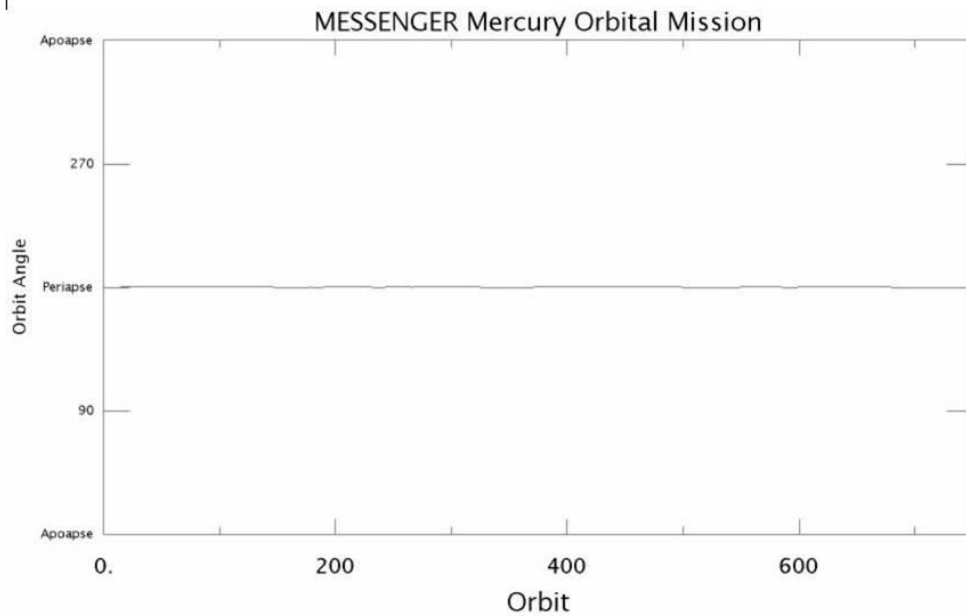
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Building G&C for the year



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Imaging Summary Statistics



2011 077T06:47:58.532-2012 073T05:45:15.031

N Image = 75804

WAC(x1,x1) = 12117

WAC(x1,x2) = 0

WAC(x2,x1) = 16681

WAC(x2,x2) = 24469

N WAC = 53267

NAC(x1,x1) = 5214

NAC(x1,x2) = 0

NAC(x2,x1) = 17323

NAC(x2,x2) = 0

N NAC = 22537

N Monochrome = 32873

N Color = 41576

N Stereo = 19021

N Pivot Step = 2616.3205300824275

N Filter Step = 98524

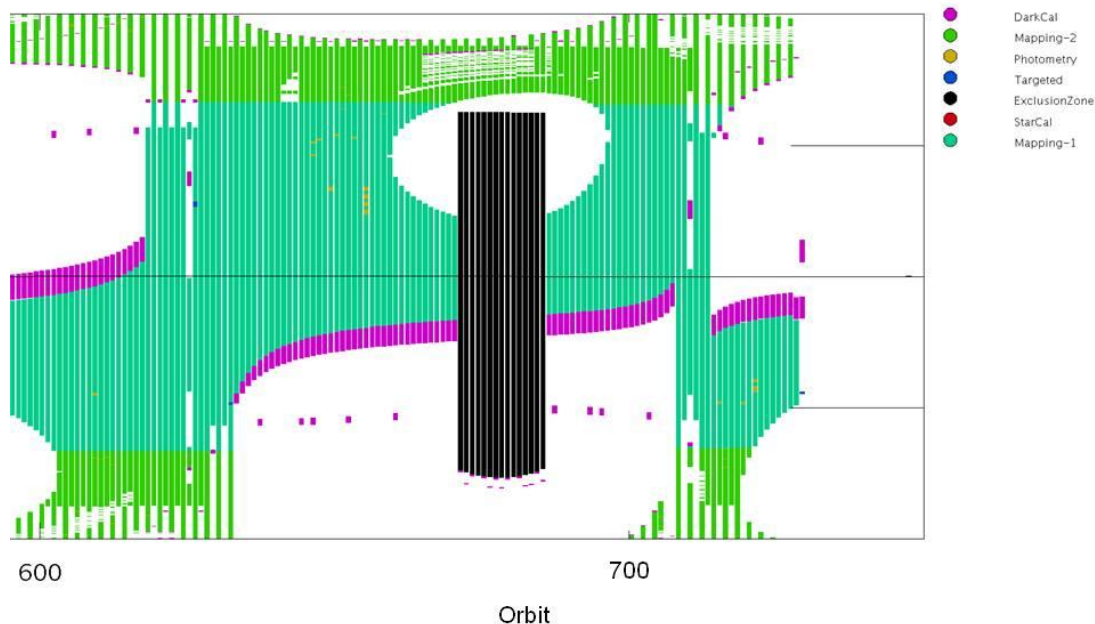
N Command = 202929

N Pivot move command = 35885

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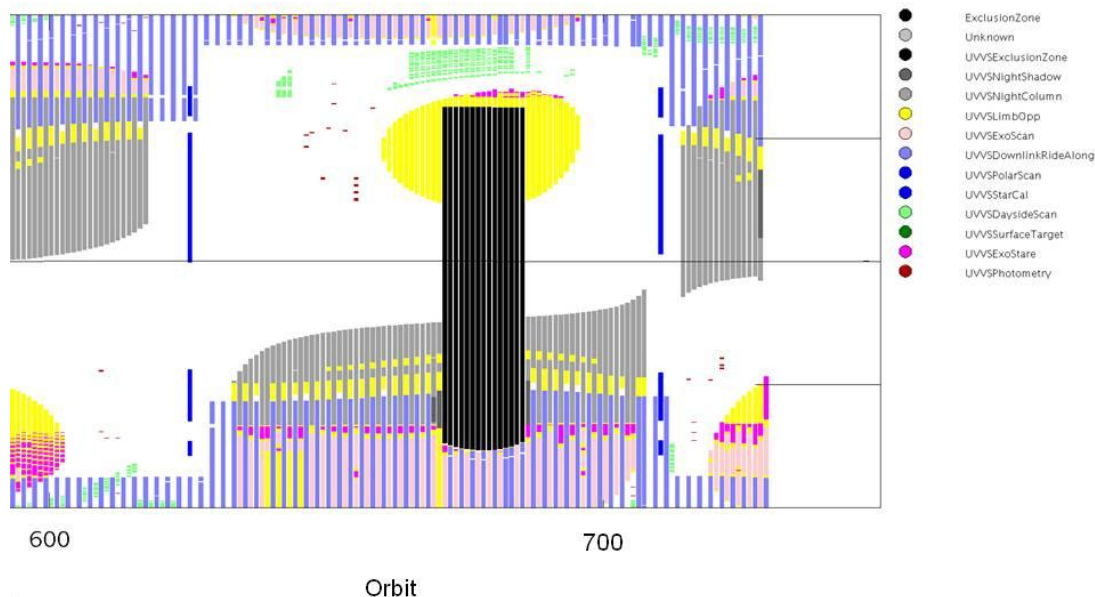
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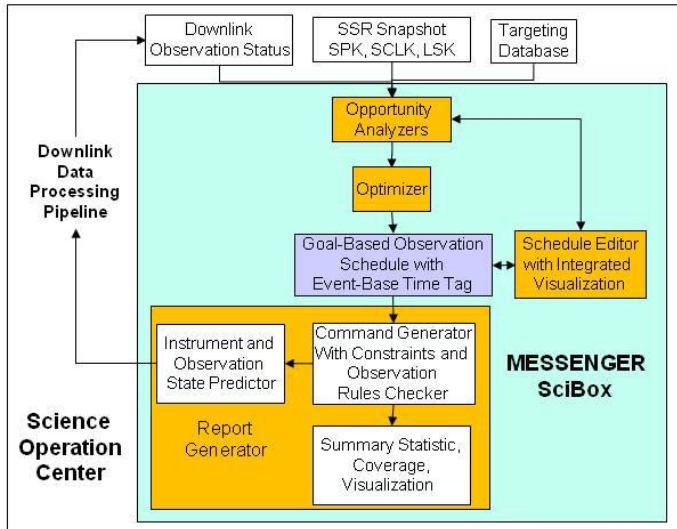
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Overall SciBox Structure



Inputs

- Predicted trajectory
- Targeting database
- Downlink observation status

Outputs

- Predicted State for downlink autonomous detection
- Commands for uplink to spacecraft
- Summary and plots for evaluation

Four subsystems

- Opportunity Analyzers
- Optimizer
- Editor Tools
- Report Generator

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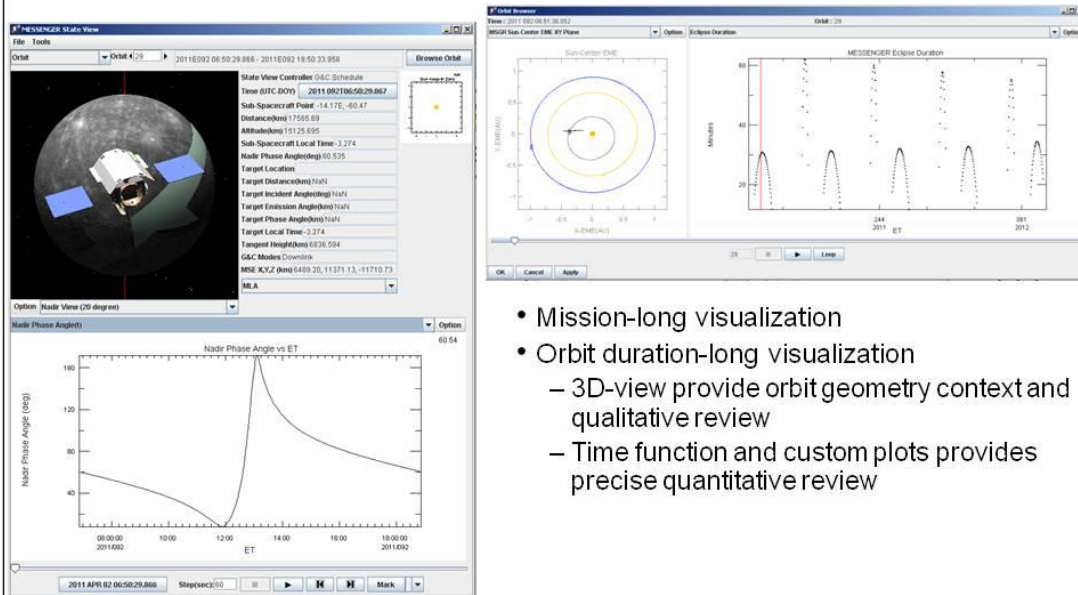
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SciBox: State View



Mission-long visualization

Orbit duration-long visualization

- 3D-view provide orbit geometry context and qualitative review
- Time function and custom plots provides precise quantitative review

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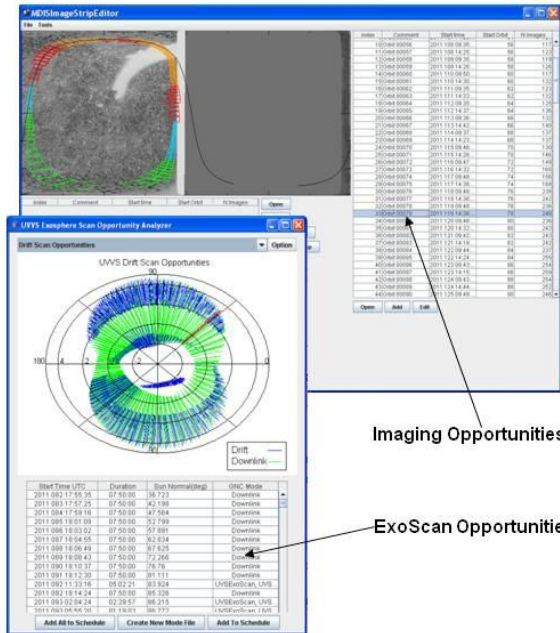
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Opportunity Analyzers



- Search-engine driven
- Algorithms defined by instrument concepts of operations
- Accommodates user-defined search criteria
- Schedules derived for entire mission
 - Evaluates observations against desired criteria (e.g. altitude, range, angles)
 - Compliant to spacecraft operational constraints
 - SKI constraints
 - Instrument operation mode constraints

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Optimizer



1st Solar Day	2nd Solar Day
Eclipse	Eclipse
Orbit Correction Maneuver	Orbit Correction Maneuver
Mercury Orbit Insertion	G&C High Rate
G&C High Rate	Downlink - High Gain Antenna
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UVVS Star Calibration	UVVS Star Calibration
XRS Star Calibration	XRS Star Calibration
MDS Limb Scan/Pivot Cal	MDS Limb Scan/Pivot Cal
UVVS Limb Scan	UVVS Limb Scan
Priority-3 Targets & VIRS phot 3	Priority-3 Targets & VIRS phot 3
XRS/VIRS Global Mapping	XRS/VIRS Mapping
MDIS Global Color Mapping	Priority-4 Targets & VIRS phot 4
MDIS Global Monochrome Mapping	UVVS Exosphere Scan
Priority-4 Targets & VIRS phot 4	MDIS North Polar Ride-Along
UVVS Exosphere Scan	MAG Observation
MAG Observation	GRS Northern Hemisphere Coverage
GRS Northern Hemisphere Coverage	NS Northern Hemisphere Coverage
NS Northern Hemisphere Coverage	EPS Observation
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RS - Low Gain Antenna	Priority-5 Ride-Along Targeted Observations
Priority-5 Ride-Along Targeted Observations	Priority-6 Ride-Along Targeted Observations
Priority-6 Ride-Along Targeted Observations	Priority-7 Ride-Along Targeted Observations
Priority-7 Ride-Along Targeted Observations	

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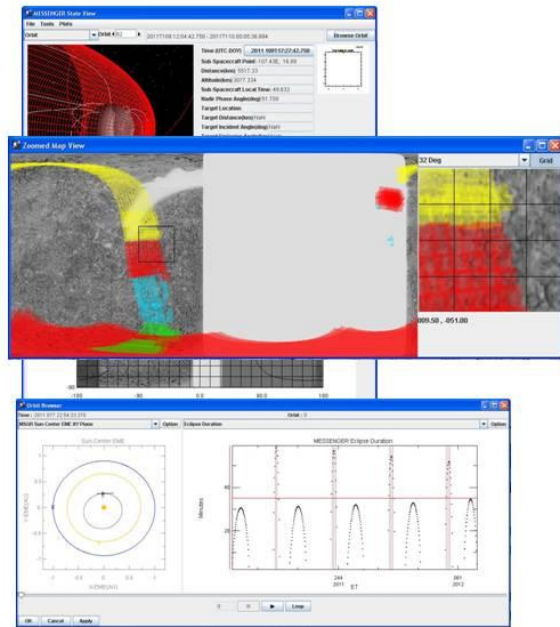
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Visualization & ReviewTools



- Map projection views
- 3-D geometry views
- Foot-print and bore-sight views
- Spatial scales from image pixel to astronomical unit
- Time scales from seconds to years (mission duration)

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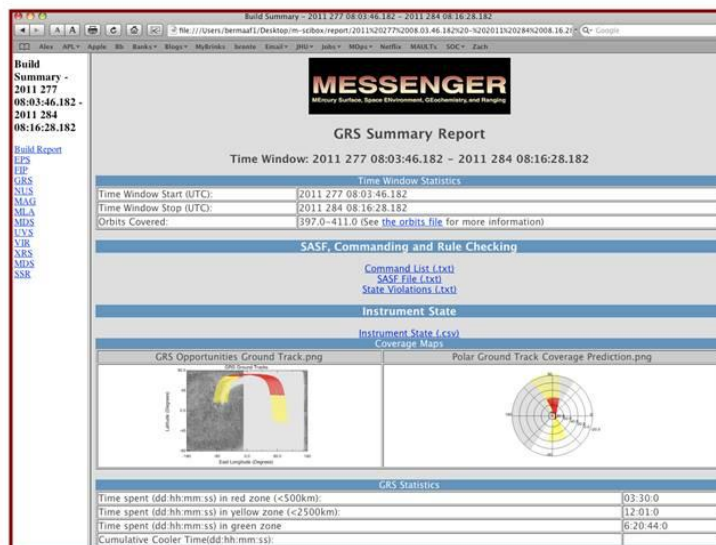
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Instrument Report Interface



Summary reports provided for each Instrument include:

- Instrument commands (as SASF)
- Graphs of coverage and ground track
- Rule violations
 - Operational constraints
 - Observation objectives
- Resource usage



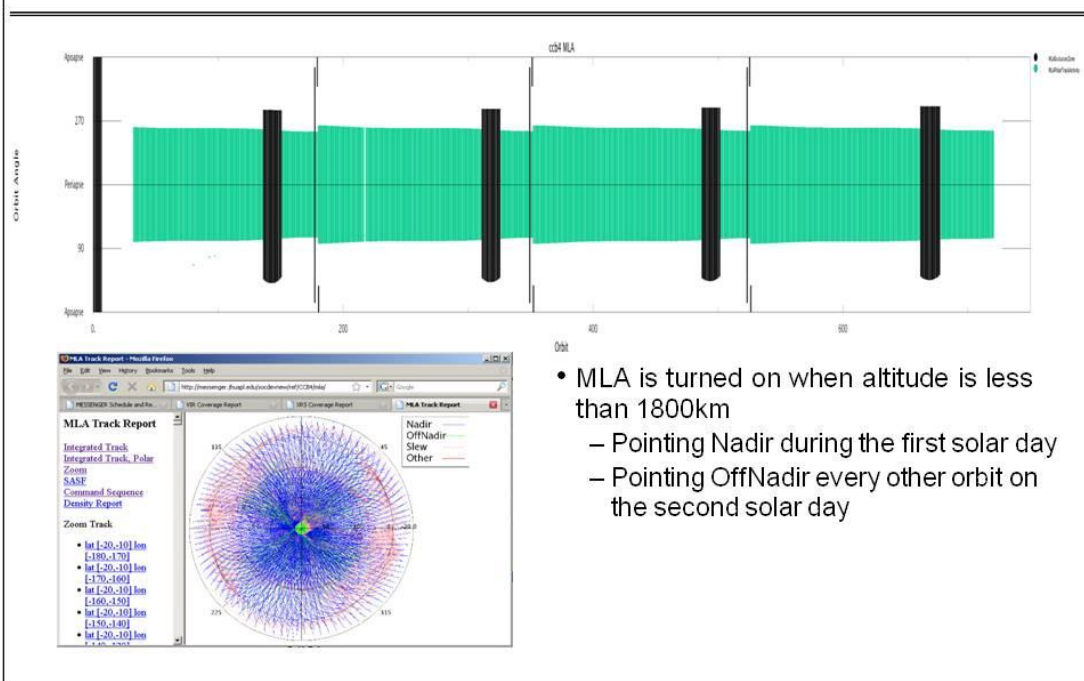
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SciBox: MLA Schedule View



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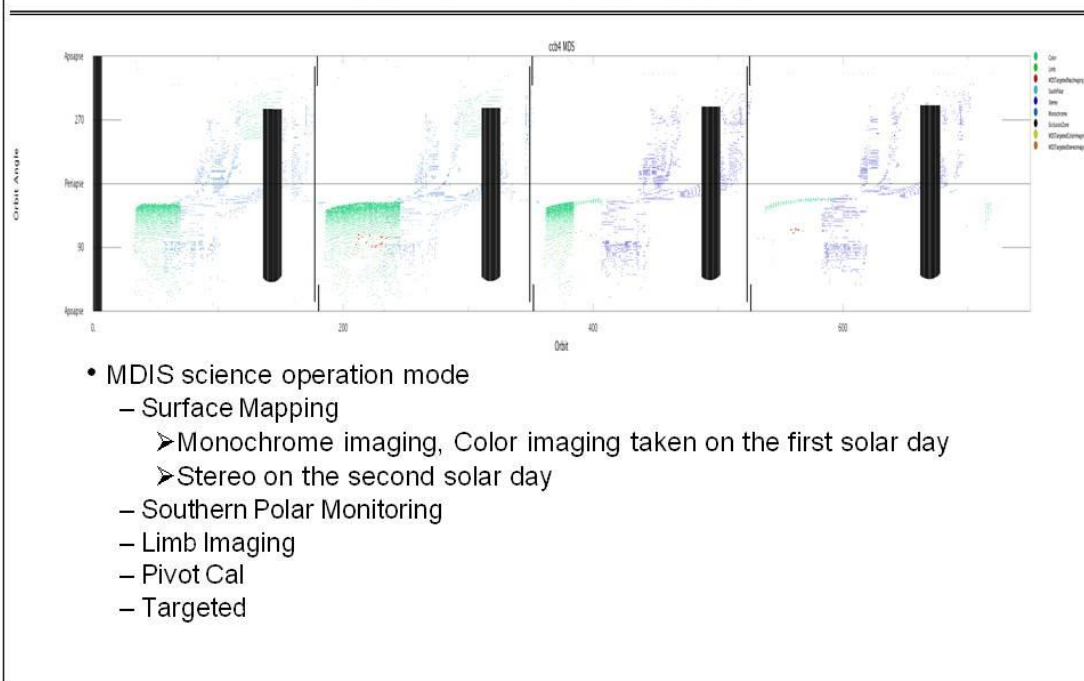
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SciBox: MDIS schedule



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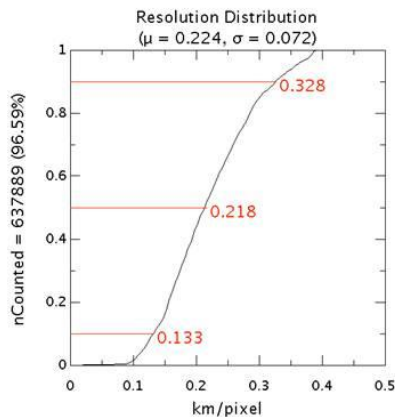


MESSENGER

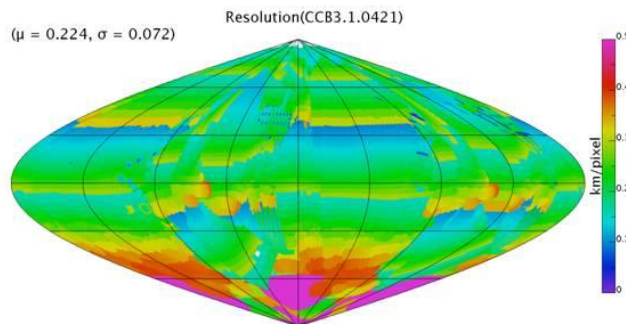


Sample Output: Monochrome Basemap

- PLR: Global monochrome map with >90% coverage at 250 m/pixel average resolution



>96% coverage at 224 m/pixel average resolution



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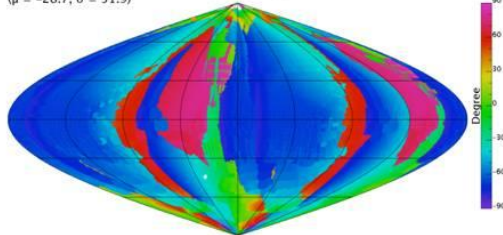


Sample Output: Monochrome Basemap

- In addition, want neighboring images to be taken from similar illumination conditions as much as possible

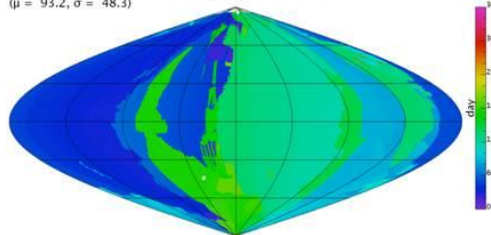
Monochrome LocalTime Angle(CCB3.1.0421)

($\mu = -28.7$, $\sigma = 51.9$)



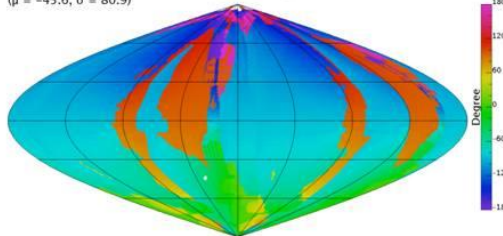
Imaging Time(CCB3.1.0421)

($\mu = 93.2$, $\sigma = 48.3$)



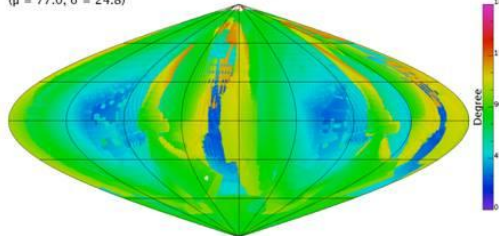
Monochrome SolarAzimuth Angle(CCB3.1.0421)

($\mu = -45.6$, $\sigma = 80.9$)



Monochrome Phase Angle(CCB3.1.0421)

($\mu = 77.0$, $\sigma = 24.8$)



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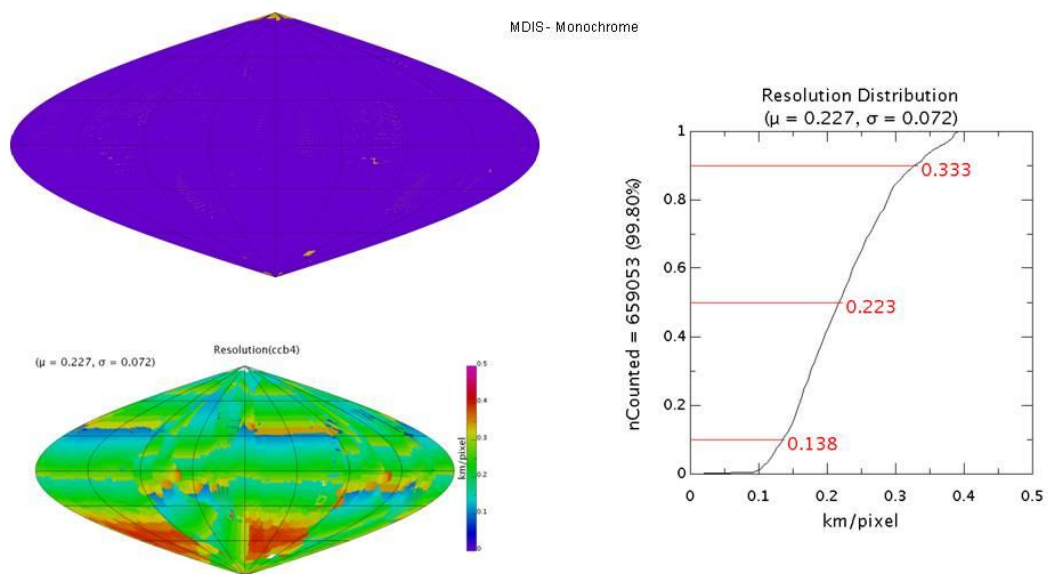
60



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SciBox Verification – Coverage (1)



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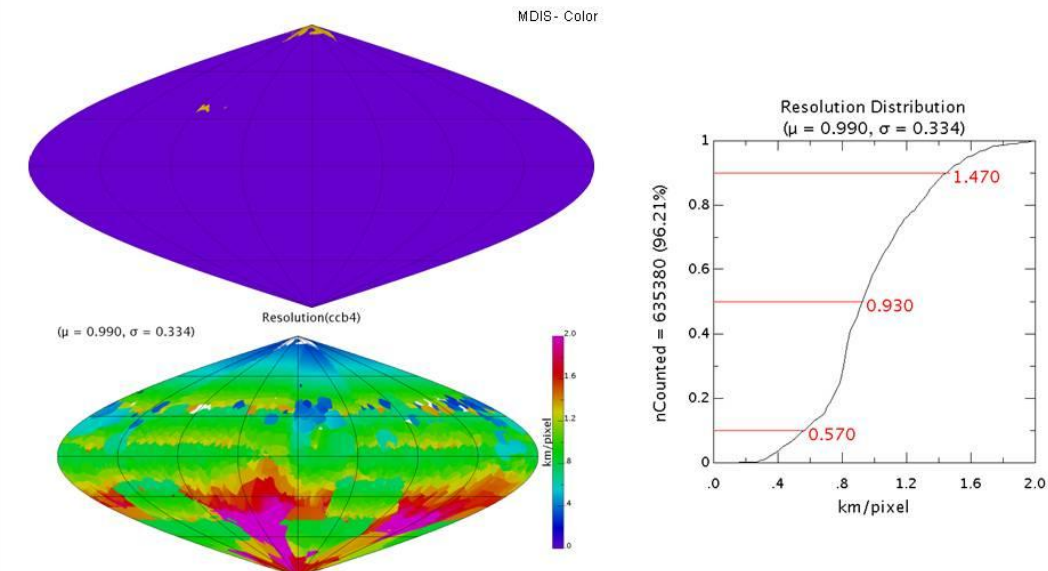
-61



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SciBox Verification – Coverage (2)



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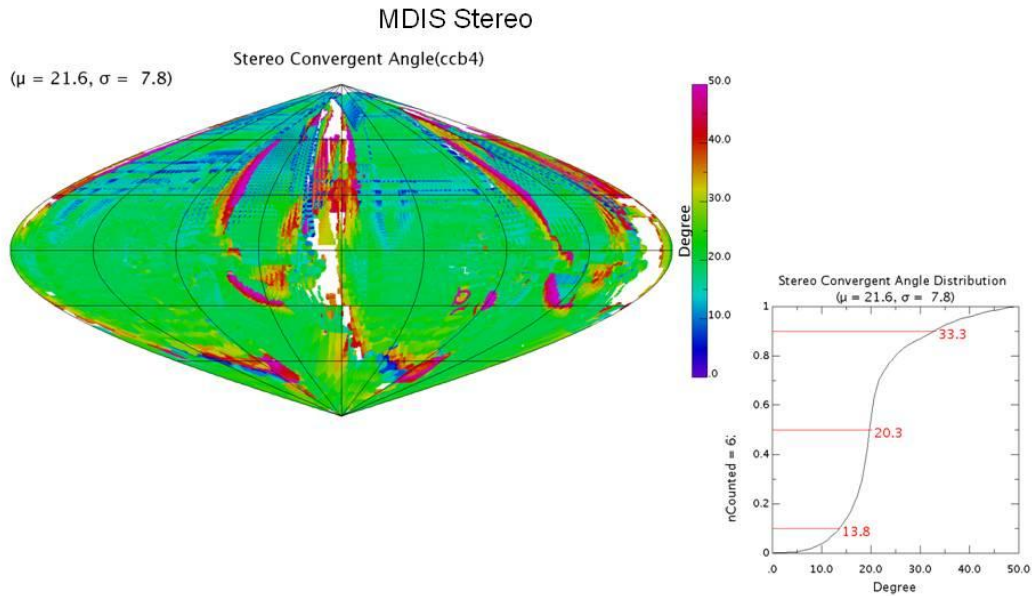
-62



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SciBox Verification – Coverage (3)



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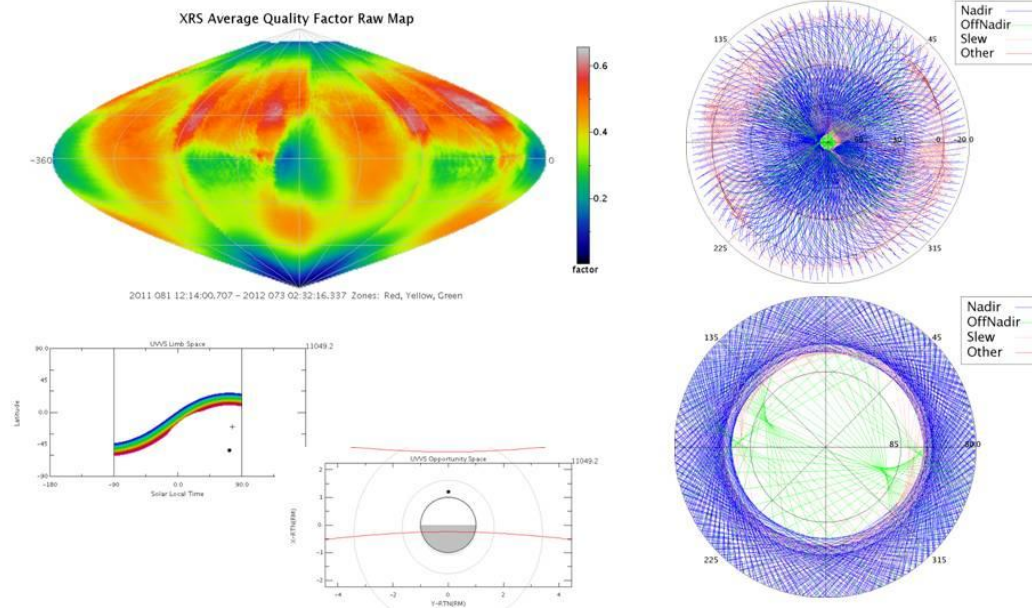
63



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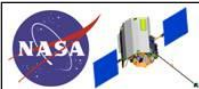
SciBox Verification – Coverage (4)



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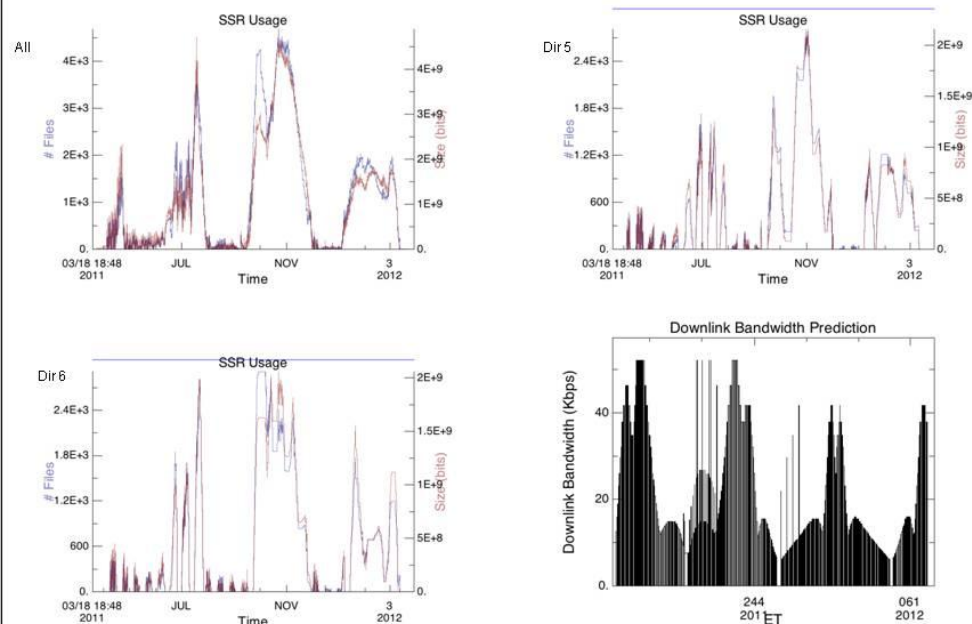
64



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SciBox Verification – SSR Resources



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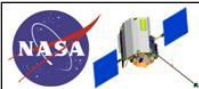
Advance and Near-Term Planning

- Two distinct science planning tasks in orbit operations
 - Advance Science Planning (ASP): Adjustments in orchestrated mission-long science observation plan
 - Near-Term Science Planning (NTSP): Convert observation plan to executable command sequences
- ASP objectives
 - Respond to actual orbit: MOI, OCMs
 - Respond to actual SC performance: power, G&C, RF, SSR
 - Respond to contingencies: SC safing, instrument anomaly, ...
 - Respond to discoveries
 - All science G&C commanding is scheduled in the ASP process
- NTSP objectives
 - Convert science observation schedule to MOPs-ready activity requests
 - Verify science commanding with operational tools
 - Integrate into command load

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ASP & NTSP



Advance Science Planning (ASP)

- **Long-range planning** of entire orbital mission.
- Primary tool: **SciBox**
- Output: **Baseline Plan** (every 5 weeks)



Near-term Science Planning (NTSP)

- **Short-term scheduling:** building weekly command loads.
- Primary tools: **SciBox, JIRA**
- Payload output: **SASFs** (due weekly).

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ASP - NTSP Relationship



ASP: Advance Science Planning
NTSP: Near-Term Science Planning
MOM: Mission Ops Mgr.
MOPs: Mission Operations
POM: Payload Ops Mgr.

The Baseline is revised every 5 weeks.

A# = ASP delivery #
N# = NTSP week #

Week	1	2	3	4	5	6	7	8	9	10	11	12	13
Process Steps	A1					A2					A3		
1. ASP delivers Baseline A#	A1					A2					A3		
2. MOPs delivers Initials for N#	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
3. POM ingests MOPs Initials, posts schedules	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
4a. Teams review, approve schedules	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
4b. G&C team runs sims	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
5. POM verifies sched file approvals	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
6. Instr, RS teams create, review SASFs	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
7. G&C team completes sims; advise results	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
8. Teams generate, deliver SASFs, approvals	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
9. POM verifies SASFs; delivers to MOPs	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
10. MOPs builds Command Load; posts Timeline	A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1	A3N2	A3N3
10. MOPs completes Command Load			A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1
11. MOPs holds review, uplinks Command Load to spacecraft			A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1
12. Command Load executes			A1N1	A1N2	A1N3	A1N4	A1N5	A2N1	A2N2	A2N3	A2N4	A2N5	A3N1

- **Five weekly command loads built per each ASP delivery; a new command load is started each week.**
- Each week:
 - POM, Instrument, G&C, RS teams are working on two different command loads (weeks N and N-1).
 - MOPs is building, reviewing, and uplinking one command load (week N-2).
 - One command load is executing (week N-3).

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ASP Process



1. Accumulate recommendations/requests via JIRA: to ASP-lead for initial vetting/clarification (ongoing task, pick up active requests at ASP cycle start).
2. Requests reviewed by core team: PI, PM, PS, DPS (2), MSE. Approve for analysis, refer to Science Steering Committee, or defer.
3. Analysis:
 - Directed by ASP-lead;
 - Conducted by ASP-lead, instrument scientists, and SciBox developers.
 - May include extended analysis of requests held over from prior ASP cycles.
 - Assess feasibility of recommendations.
 - Evaluate coverage and target acquisition status relative to expectations & requirements.
4. Report to core team: ASP-lead reports on feasibility, impact on resources, and effects on other observations.
5. Core-team decision: Y/N.
6. ASP-lead directs implementation of approved requests. (May include implementation of previously approved requests held over from prior ASP cycles.)
7. Regression testing and review of revised observation plan. (If review uncovers problems – reverting to prior ASP cycle plan is an option.)
8. Delivery of new plan & corresponding version of SciBox.

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ASP Tasks and Responsibilities



	Task	Personnel	Duration (days)	Days from start
1	Compile recommendations for adjustments	ASP-lead	1	1
2	Requests reviewed/approved	Core team	1	2
3	Analysis	ASP-lead, SciBox developers, Instrument scientists	7	9
4	Assessment report to core-team	ASP-lead	0.5	9.5
5	Implementation decision	Core team	0.5	10
6	Implementation	ASP-lead, SciBox developers	8	18
7	Testing and review	Instrument teams, SciBox developers	5	23
8	New ASP delivery	SciBox Developers	2	25

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ASP Timeline



	Sun	Mon	Tue	Wed	Thu	Fri	Sat
W1		T1	T2	T3: Analysis			
W2		T3: Analysis				T4 & T5	
W3		T7: Implementation					
W4		T7: Implementation			T8: Testing/Review		
W5		T8: Testing/Review			T9: Delivery		

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ASP Interfaces (1/2)



- Change requests
 - Submissions: normal communications & JIRA logged in JIRA
 - Approved tasks logged in Trac
- MOPS and mission design
 - Mission design
 - Predicted SPICE kernels (spk) files
 - OCM schedule: file
 - Downlink tracks - DSN schedule
 - 0-8 weeks out: saf negotiated schedule file
 - 9-weeks to EOM: SciBox generated COM report.....file
- MSE: sub-system performance monitoring
 - Normal communications
 - Specific SciBox input files & parameters
 - Downlink rate profile:..... file
 - Eclipse time exclusion windows: parameters
 - Maximum model slew rate: parameters
 - SKI constraints: parameters
 - Instrument frame kernels: files

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ASP Interfaces (2/2)



- Science team
 - Normal communications
 - XRS flare-count/day..... parameters
 - MDIS max. exposure setting..... parameters
 - MLA ranging altitude..... parameters
 - Red/Yellow/Green rates (GRNS, XRS) parameters
 - Binning settings (VIRS)..... parameters
 - SciBox input files
 - Rate profile tables (MAG, EPS)..... files
 - Macro selection tables (MASCS)..... files
 - PIPE database
 - Target database (REACT)..... files
 - Coverage reports, maps (REACT)..... files
- MDIS coverage
 - Predicts: SPICE kernels & SciBox schedule..... files
 - Actuals w. DQI: PIPE..... files (EDRs)

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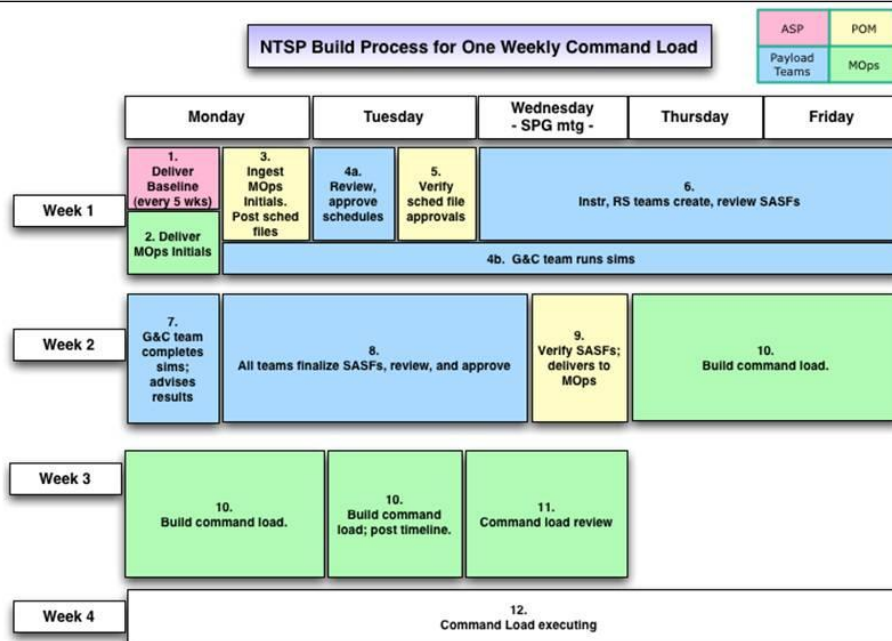
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NTSP Process: 3 weeks



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Software & Tools

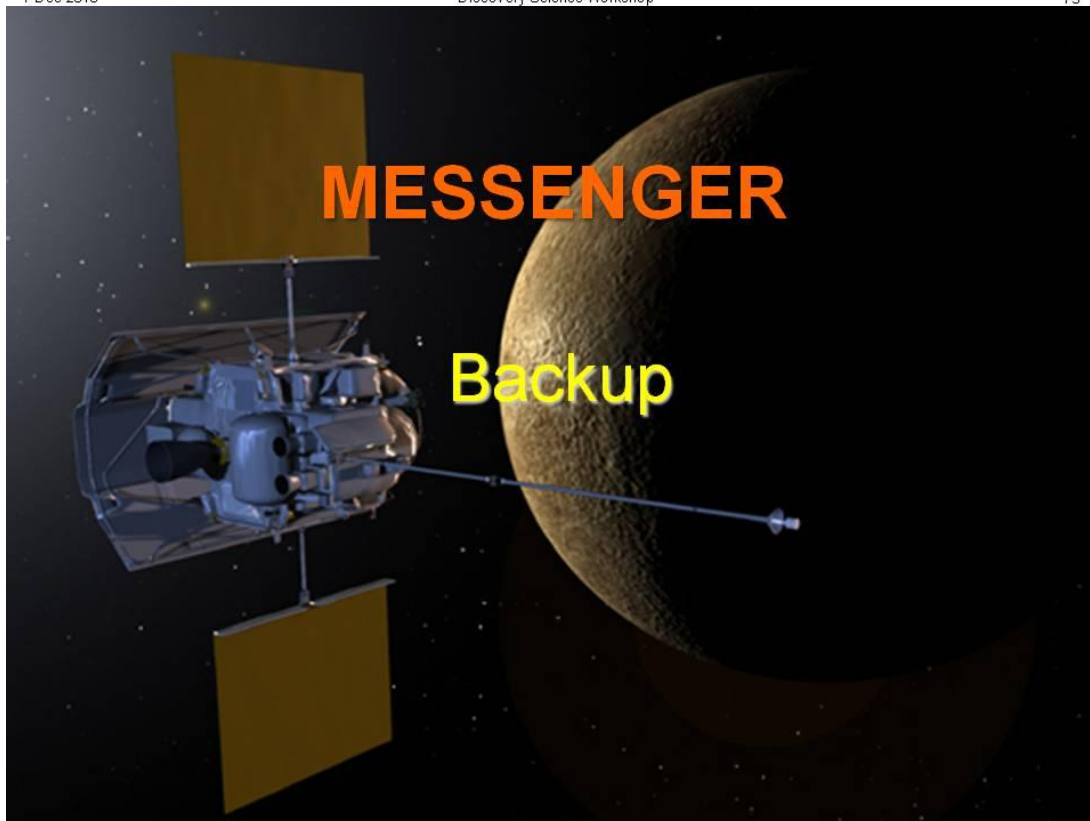


- JIRA: Revision Request
 - Commercial issue-tracking web tool (by Atlassian) customized for our use by APL Space Department
 - Used for tracking workflow and approvals through NTSP process
 - Replaces normal communications (e-mail, etc.)
 - Simple 1-step submission and notification functions
- SciBox: Primary Operational Tool
 - Java-based application developed @ APL for long-range planning, short-term scheduling
 - Payload teams use GUIs and reports to review weekly activities and generate SASFs
 - Mission simulation
 - Command request review
 - Comprehensive reports
- Trac: Scibox Change Tracking
 - Used for tracking long-term science planning development since 2008
 - No changes needed for orbit

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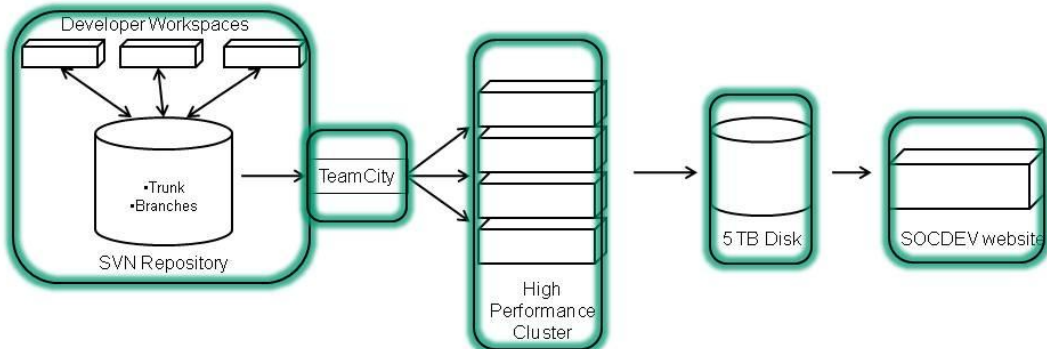




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SciBox Software Development



- Development occurs in branches. Tested and then merged back into trunk
- TeamCity can pull from branches or trunk for compilation, testing, deployment and full report generation
- High performance cluster is used to run simulations. Current time: ~3 hours. Plans to fully utilize cluster should reduce this to ~1-1.5 hours for full schedule and report generation
- 5TB of storage is used to archive all nightly runs. Archive currently runs back to 5/1/10.
- Storage disk is exported to password protected webserver so builds may be exposed to other developers and instrument/POM teams for testing.

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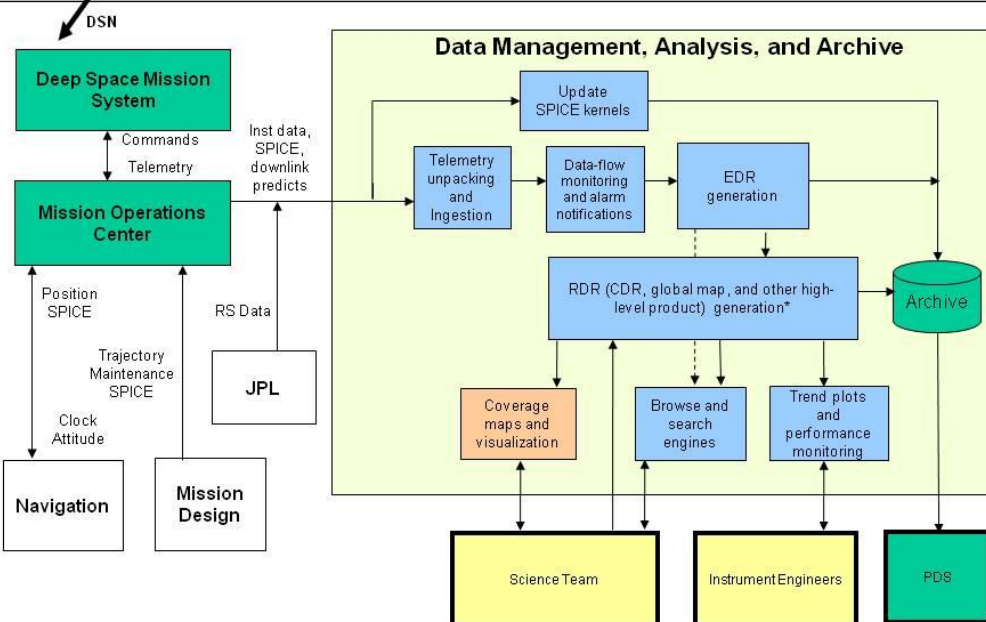
77



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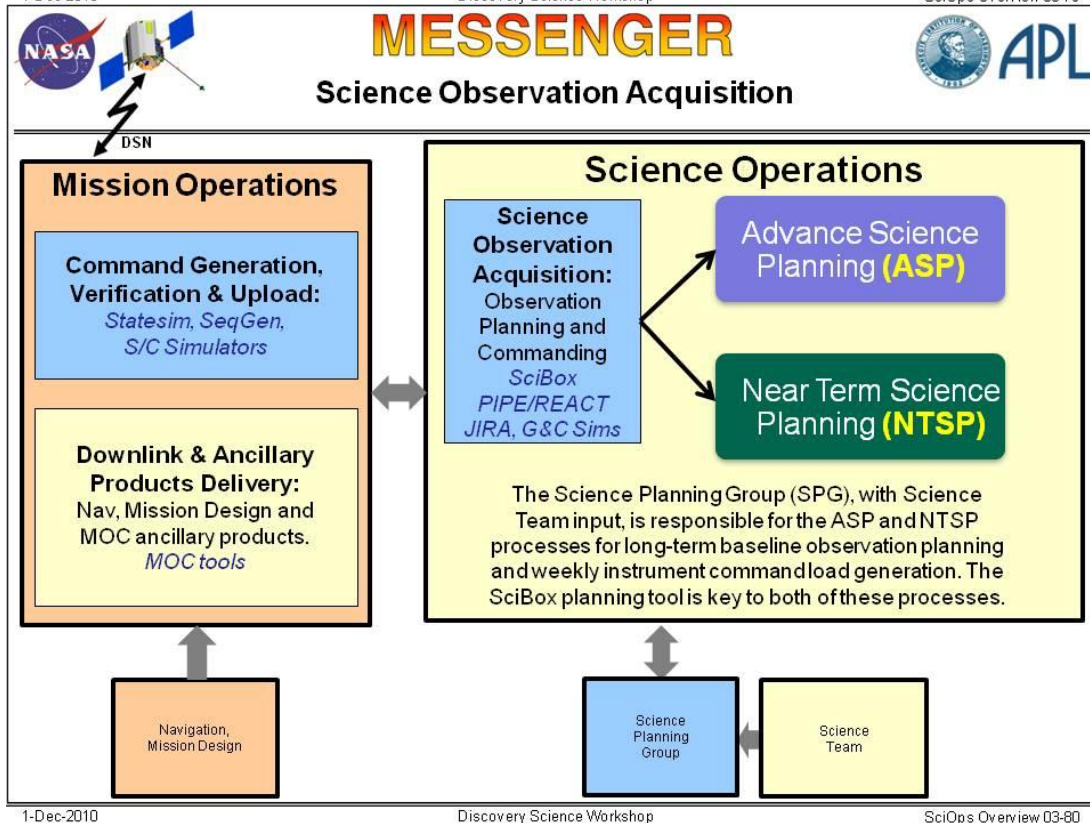
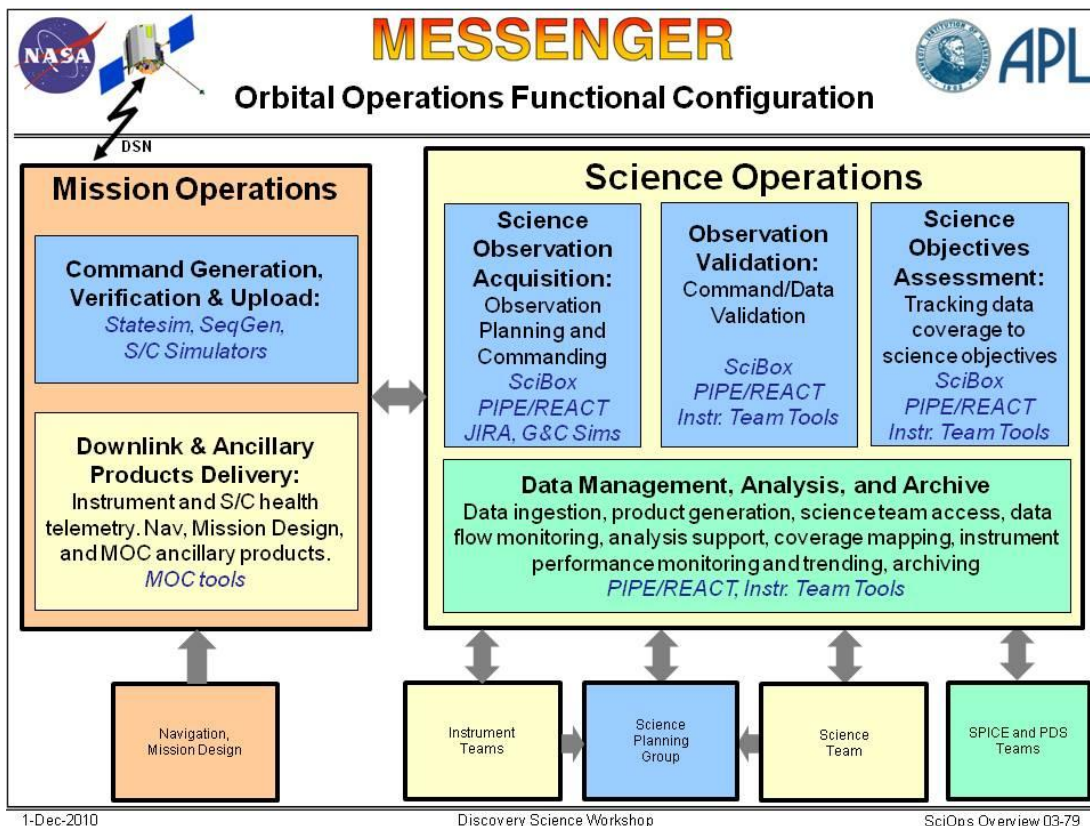
DMAA Data Flow and Interfaces

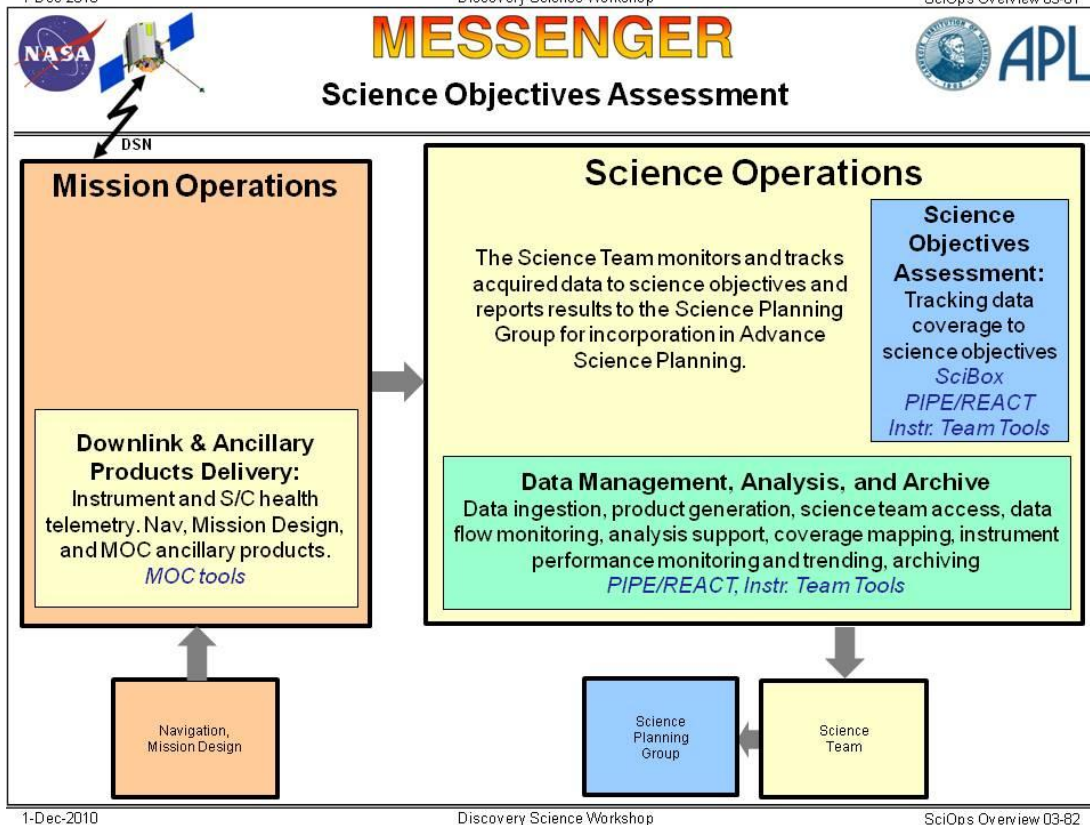
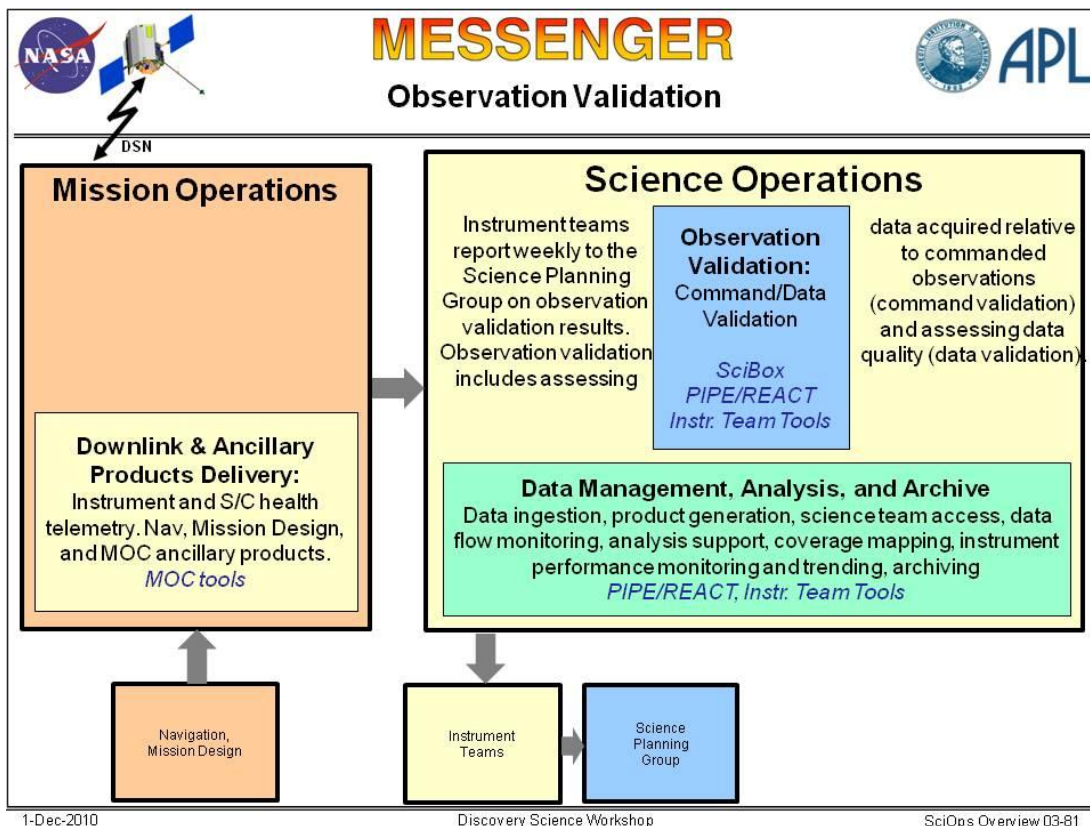


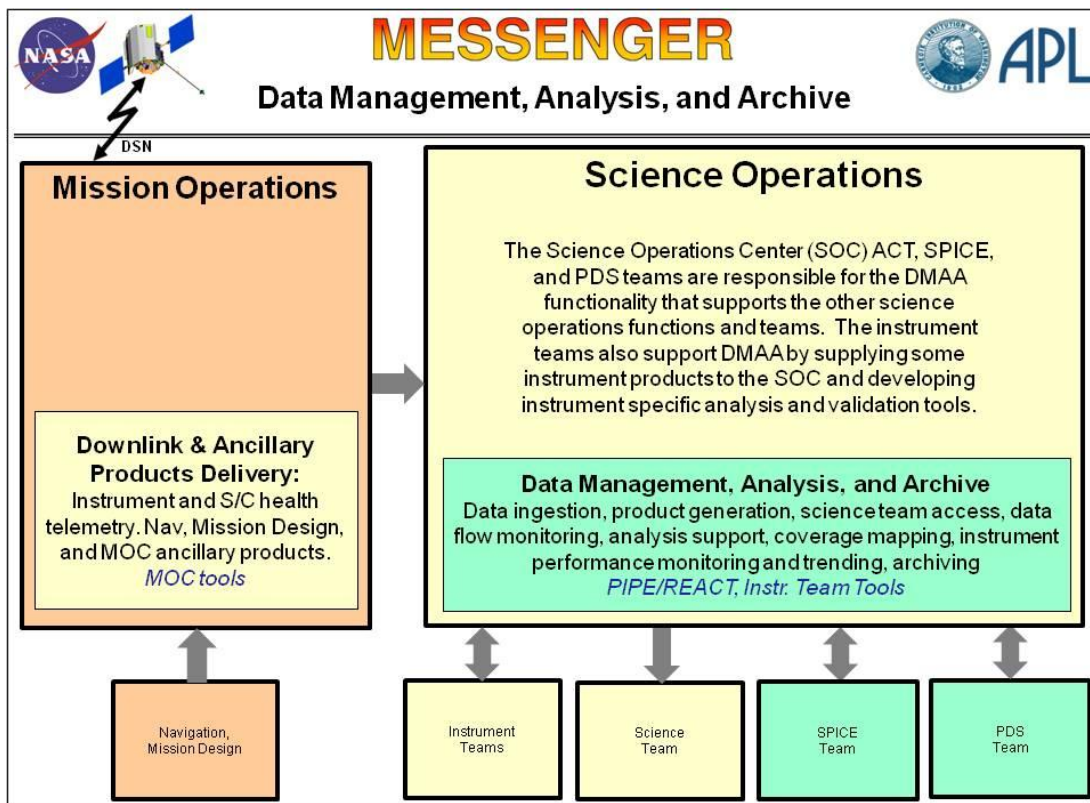
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DMAA Overview 8-78



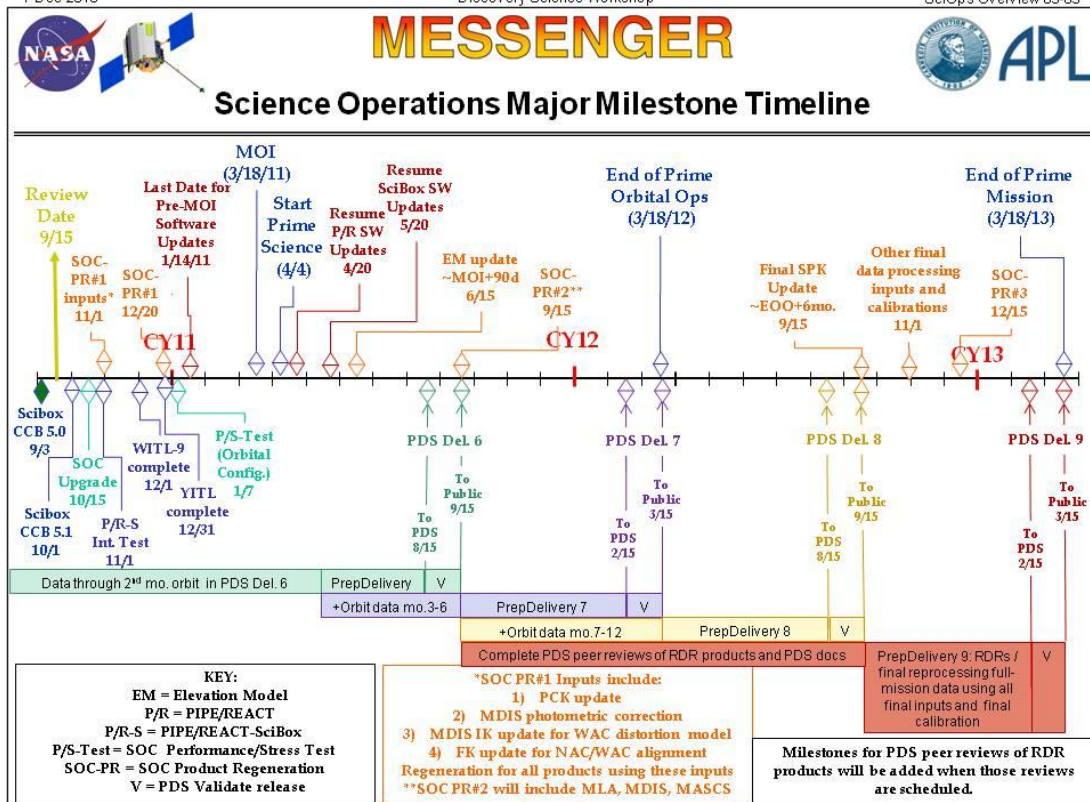




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SciOps Overview 03-83



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SciOps Overview 03-84



National Aeronautics and Space
Administration
Jet Propulsion Laboratory
California Institute of Technology



Stardust-NExT

Mission Overview and Science Planning Discussion

Tim Larson
December 1, 2010



Cornell University



National Aeronautics and Space
Administration
Jet Propulsion Laboratory
California Institute of Technology

What We Are Going to Do:



- Extend and complete the investigation of Comet Tempel 1 initiated by Deep Impact



Cornell University





How Are We Going to Do It:



Primary Objective

- Obtain 72 high resolution images around closest approach
 - Some three dozen with resolution 80 meters/pxl or better
 - Best resolution expected: 12 meters/pxl
- Achieve at least 20% overlap with DI coverage to look for surface changes between perihelion passages
- Extend DI coverage to determine extent of layered terrains, search for other sources of smooth flows, etc.
- If possible, image and determine diameter of the DI crater



Secondary Science Objectives

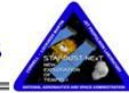


- Monitor dust production activity through imaging for 30 days before encounter
- Obtain DFMI dust measurements for ± 15 minutes around CA
- Obtain CIDA dust ion spectra for ± 1 hour around CA
- Monitor dust production activity through imaging for 30 days after encounter





Stardust-NExT Level 1 Requirements



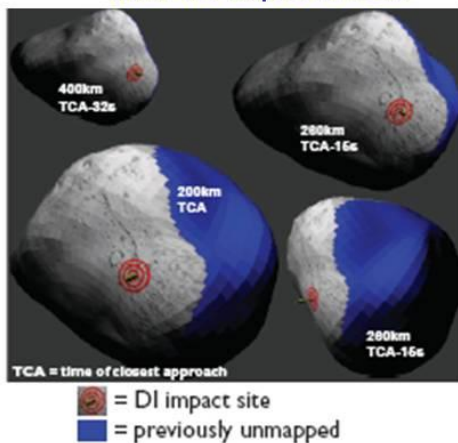
- **Baseline Requirements:**
 - Obtain approximately 70 high-resolution images, including stereo, at encounter. At least 24 (goal of 40) to have resolution of 80 m/pxl or better.
 - Image some areas of the nucleus not previously seen by Deep Impact.
 - If possible, obtain an image of the DI crater in sunlight at a scale of 20 m/pxl at an emission angle of less than 60 degrees.
 - Measure dust particle flux within 20,000 km of the comet at particle masses between 10^{-11} and 10^{-3} gm.
 - Measure dust production rates through distant imaging of the coma.
- **Threshold Requirements are:**
 - Successfully return at least one stereo image pair at a resolution of 20 m/pxl or better with a stereo separation angle between 10 and 30 degrees.
 - Image at least 25% of the hemisphere seen by Deep Impact at 80 m/pxl or better.



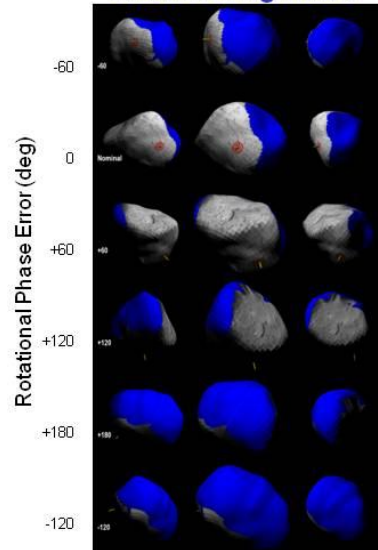
Imaging vs. Performance Floor



What We Expect to See



What We Might See





Encounter Science Sequence



- Last approach imaging block at E-42 hr
- CIDA to encounter mode at E-3 hr
- DFMI on at E-20 min
- Nominal imaging sequence runs from E-4 min to E+4 min
 - Use fastest possible NAVCAM imaging frequency around closest approach for best resolution stereo coverage
 - Spread sequence as needed to ensure covering arrival time uncertainty
 - 12 frames every 8s from E-4 min to E-2m24s
 - 48 frames every 6s from E-2m24s to E+2m30s
 - 12 frames every 8s from E+2m30s to E+3m50s
- DFMI off at E+20 min
- Begin playback of encounter images at E+3 hr (first playback completes at ~E+13 hr for 70-m DSN coverage)
- CIDA off at E+3 hr
- Second playback of encounter data from E+13 hr to E+24 hr (70-m DSN)



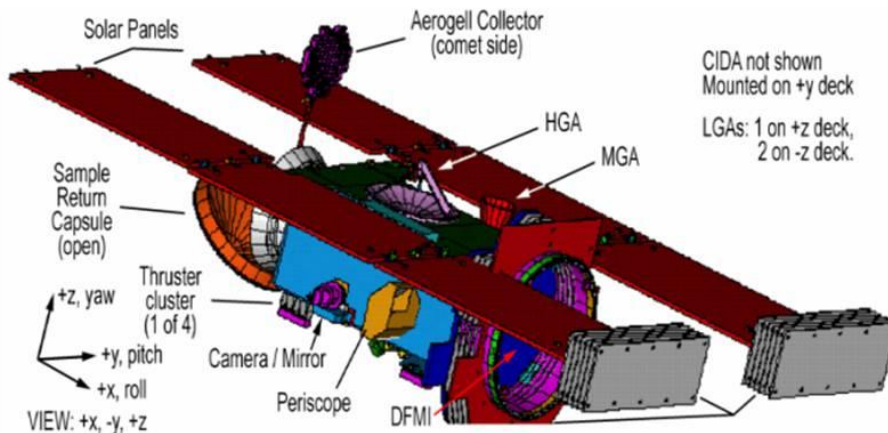
7



Stardust Spacecraft



- Launched February 1999
- Wild 2 flyby in 2004
- Sample capsule earth return in 2006



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Science Planning



- Challenges
 - Distributed teams
 - LMA – Denver
 - JPL – Pasadena
 - Cornell – Ithaca
 - Several other locations for science team members and Co-Is
 - Science team funding/availability for early planning
- Strategies
 - Deputy PI/Science Ops Lead funded and located with project from the beginning
 - Weekly encounter planning meetings/telecons starting ~1 year before encounter
 - In addition to weekly team meetings, to concentrate on encounter planning, design, coordination, etc.
 - Two major encounter planning retreats involving entire science team and spacecraft team
 - 3 days dedicated to detailed discussion of science and operations for encounter
- Periodic science team meetings



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Science Ops



- Science team planning for flyby
 - New location for science team
 - Need
 - Work space, meeting space
 - Network access
 - Capability to quickly access and evaluate large amount of data in near real time
 - Access Science Data Centers (SDCs)
 - Primary SDC at Cornell, back-up at Umd
 - Additional back-up SDC on line at JPL during flyby
 - Subset of team to perform photometric analysis of approach images of comet to help determine brightness thresholds for Autonav software
 - Image display capability for near-real time image assessment



10



The slide features a large triangular logo on the left. Inside the triangle is a stylized Earth and Moon, with two small satellite icons. The triangle's sides are labeled with agency names: NASA, JPL, MIT, GSFC, LMSSC, and SRS. Below the triangle, the word "GRAIL" is written in large orange letters, followed by "GRAVITY RECOVERY AND INTERIOR LABORATORY" in smaller white text. Below that, "Discovery Science Workshop" is written in orange. The date "December 1, 2010" and location "Washington DC" are at the bottom left. On the right, the names and titles of the Principal Investigator and Deputy Project Scientist are listed. A small disclaimer is at the bottom center.

GRAIL Overview

Maria T. Zuber
Principal Investigator

Sami W. Asmar
Deputy Project Scientist

Discovery Science Workshop

Washington DC
December 1, 2010

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Thermal Evolution: Heat sources and heat loss

External

Heating

- Impacts

Cooling

- Radiation



Internal

Heating

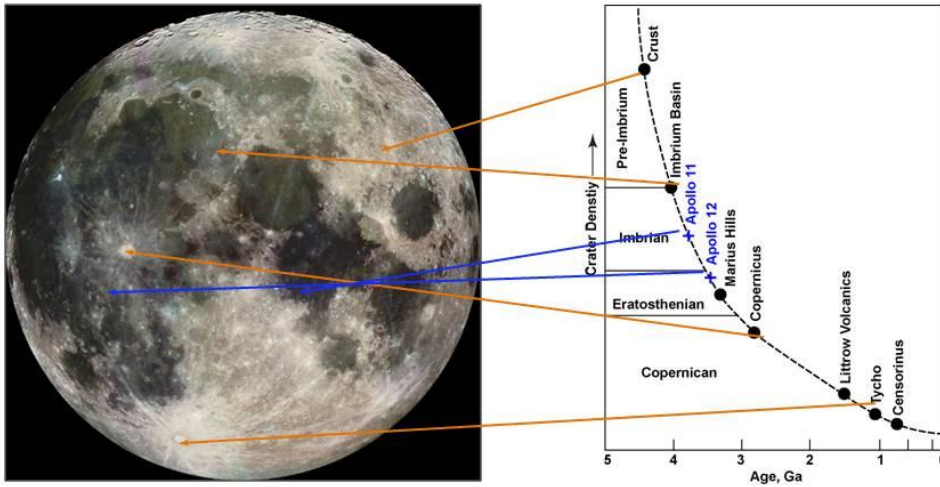
- Differentiation
- Radioactive heating

Cooling

- Conduction
- Convection
- Plumes

➔ *Reconstruct source/sink contributions throughout geologic time.*

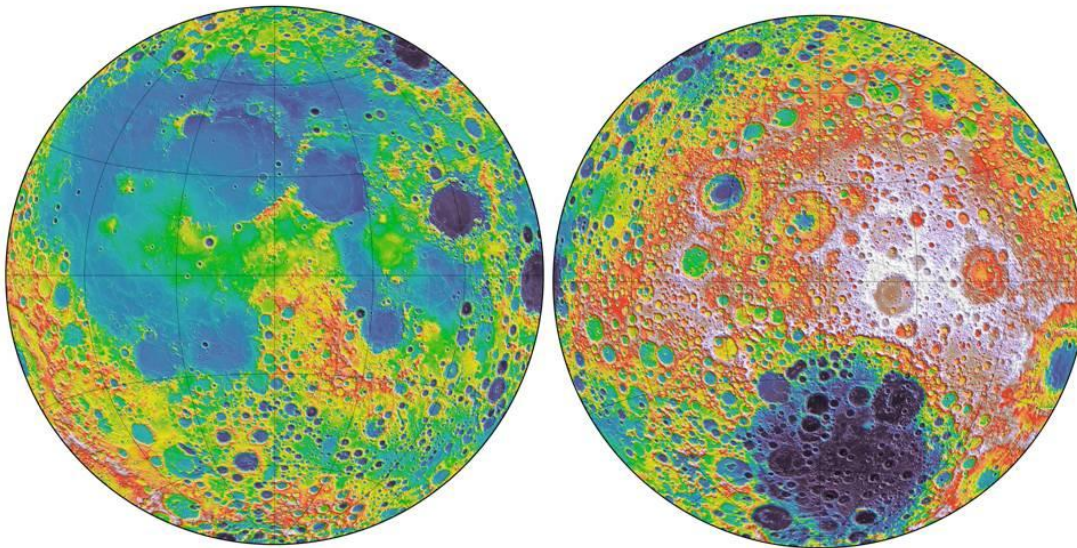
Relative and absolute chronologies



- Plot cumulative number of craters of various sizes to estimate relative ages of surfaces
- On surfaces where craters have been counted, relative ages can be “anchored” using absolute ages from Apollo samples
- Moon is only terrestrial planetary body besides Earth that has *absolute chronology*

Science and Mission Overview—Maria Zuber

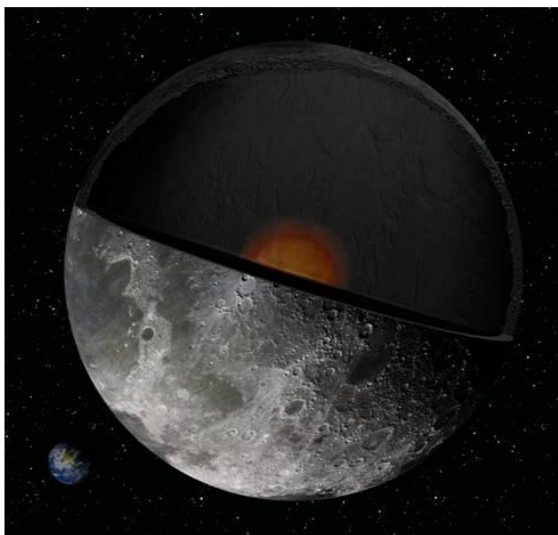
Synergy with other lunar data sets



LOLA: Over 3 billion valid measurements of lunar elevation.

Smith et al. [2010]

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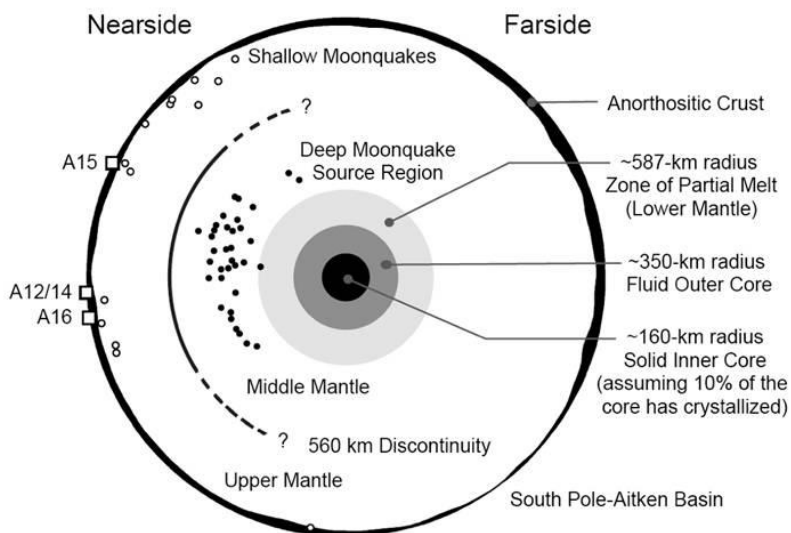


There is no greater
agony than bearing an
untold story inside you.

-- Maya Angelou

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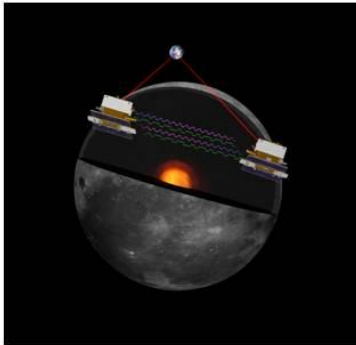
Schematic: Current understanding of lunar interior



Wieczorek et al. [2006]

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Science objectives



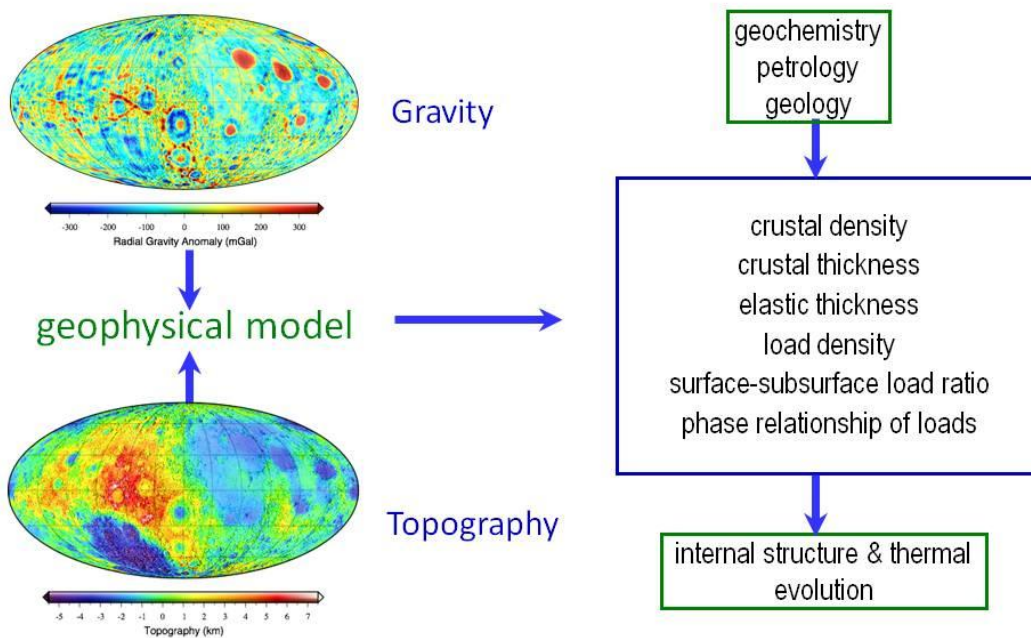
- Primary objectives:
 - Determine the structure of the lunar interior, from crust to core
 - Advance understanding of the thermal evolution of the Moon
- Secondary objective:
 - Extend knowledge gained from the Moon to other terrestrial planets

Science Investigations: (Science Floor: 1-4)

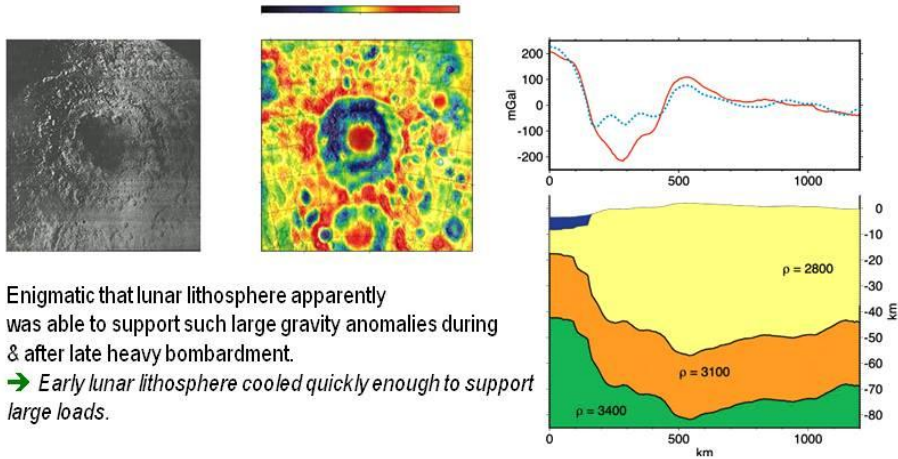
1. Structure of lunar crust and lithosphere
2. Asymmetric thermal evolution
3. Subsurface structure of impact basins and origin of mascons
4. Temporal evolution of crustal brecciation and magmatism
5. *Interior structure from lunar tides*
6. *Constraints on whether Moon has an inner core*

→ Objectives unchanged since Step 1 proposal.

Gravity and topography



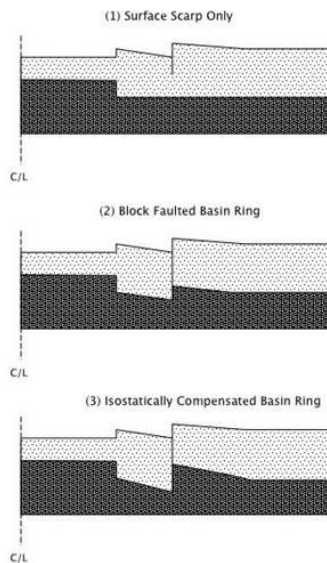
Early cooling of lithosphere from structure of impact basin



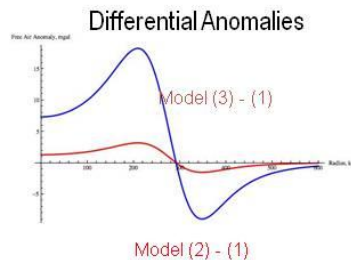
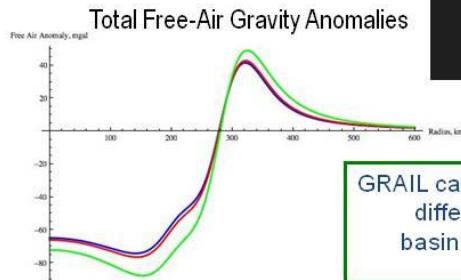
Neumann et al. [1996]; Wieczorek and Phillips [1997]

Oriente Basin: Oblique view of Oriente along with gravity from Model LP 150Q. Panels (right) show gravity predicted by flexural model with $T_e = 50$ km assuming a dual-layered crust (yellow, orange).

Basin ring formation



Oriente Model: Basin diameter = 400 km, Crust density = 2900 kg/m³, Mantle density = 3900 kg/m³, Basin depth = 3 km, Scarp height = 6 km, Crust thickness = 50 km.



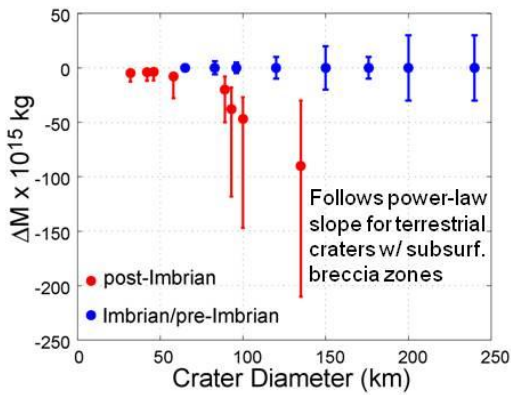
GRAIL can discriminate different models of basin ring formation

GRAIL resolution: less than line width!

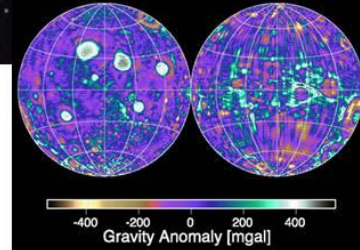
10

11

Magmaism and brecciation



Bouguer LOS gravity calculated for 8 post-Imbrian craters & 8 older, unfilled craters & converted to mass anomalies. LOS free-air gravity was obtained from Doppler tracking data from Apollo 14-17 CSMs, A16 LEM, and A15-16 sub-satellites. S/C altitude ranged from 15 to 80 km. Topography from Apollo LTOs & (mainly) Earth-based radar. From Dvorak [1979].



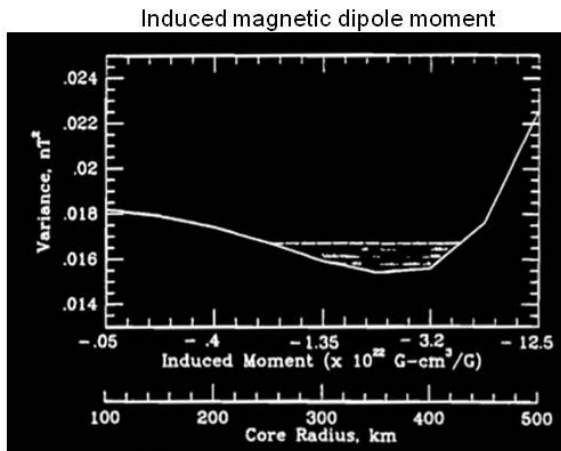
Konopliv et al. [2001]

- Apollo-era gravity analysis of 16 lunar craters. Post-Imbrian craters show mass deficiency in subsurface, whereas older, unfilled craters show ~zero mass deficiency.
- Hypothesis is that craters formed w/ breccia zones that were magmatically sealed during Moon's volcanic era.
- Analysis was hampered by small data set & errors in gravity & topography.

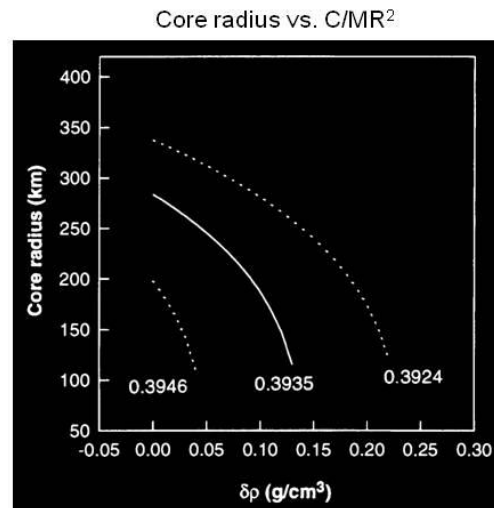
→ GRAIL can test this hypothesis, including role of compensation, with a global high-resolution, high-precision data set, and, if valid, can map out magmatic history of lunar crust in space and time.

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Deep interior: Evidence for a core



Hood et al. [1999]

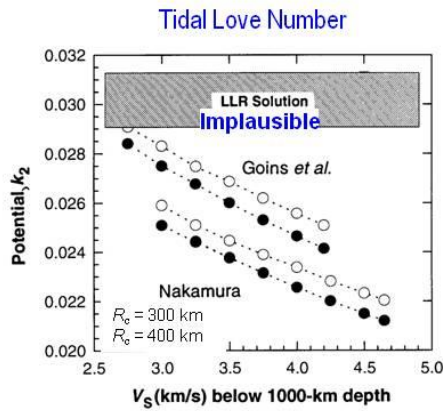


$$C/MR^2 = 0.3940 \pm 0.0019$$

$$220 < R_{\text{Max_core}} < 350 \text{ km}$$

Dickey et al. [1994]

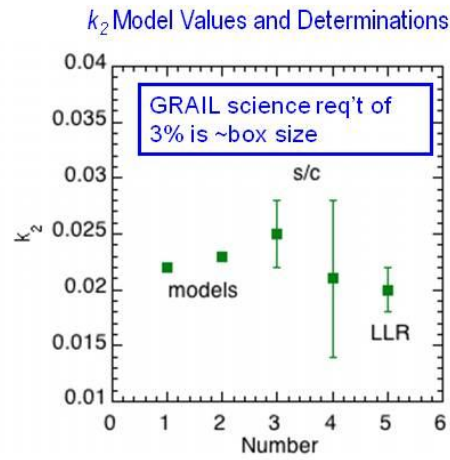
Deep Interior: State



$$k_2 = 0.0302 \pm 0.0012$$

→ fluid in deep interior?

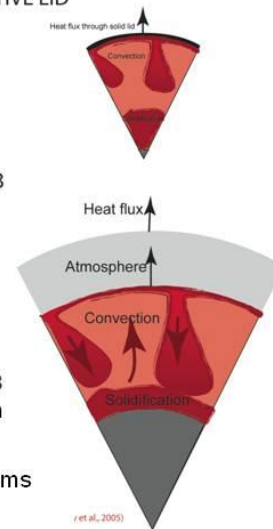
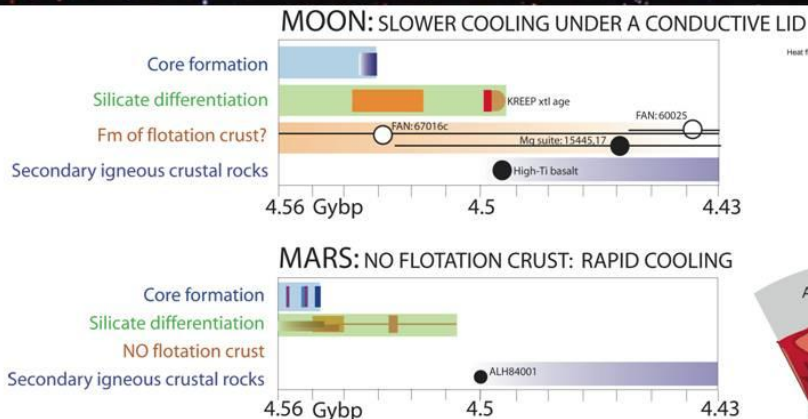
Dickey et al. [1994]



Konopliv et al. [1993]
Goossens and Matsumoto [2008]

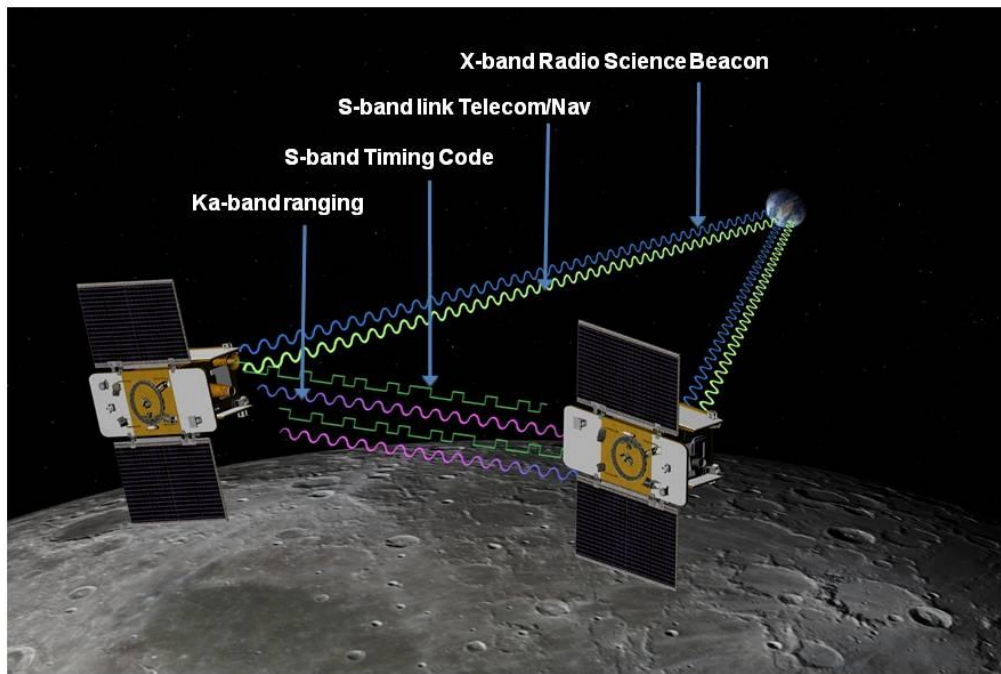
14

Comparative planetology

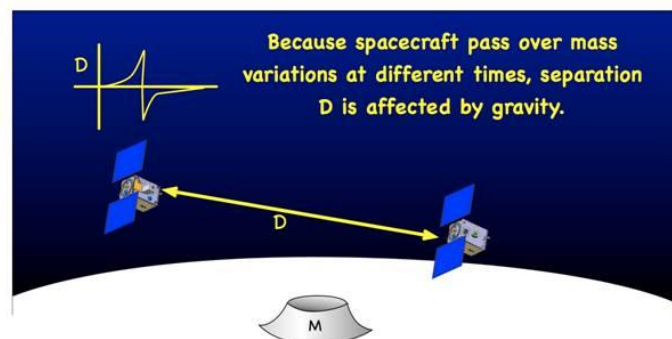
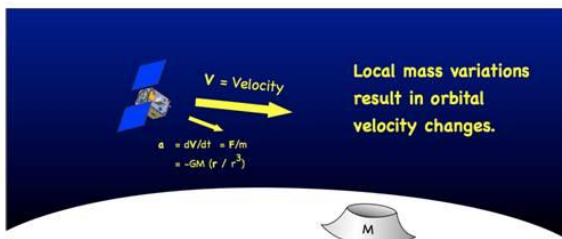


- Distinguishing models of thermal evolution becomes possible with understanding of internal structure
- Timelines for differentiation events as measured by isotopic systems
- Moon took as long to solidify than did the much larger Mars
- Due to the reduction in heat flow produced by conductive plagioclase lid
- Working on self-consistent models for lunar magma ocean solidification under a growing plagioclase lid, and will compare time scales and compositions from the forward model with data from the Moon

GRAIL concept

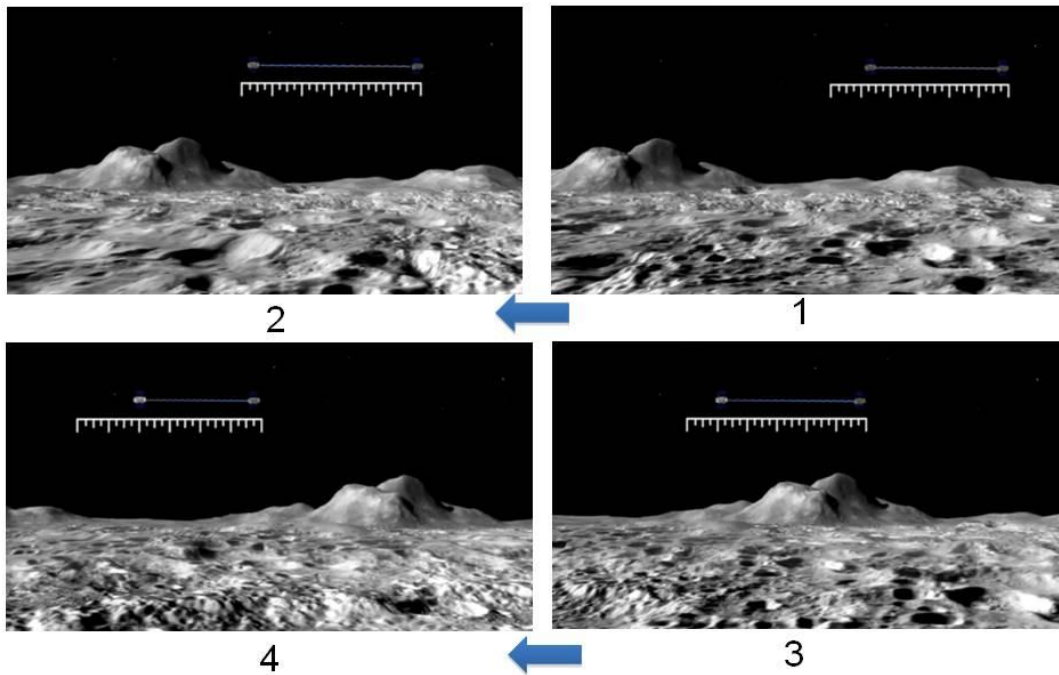


Spacecraft as sensor of gravity

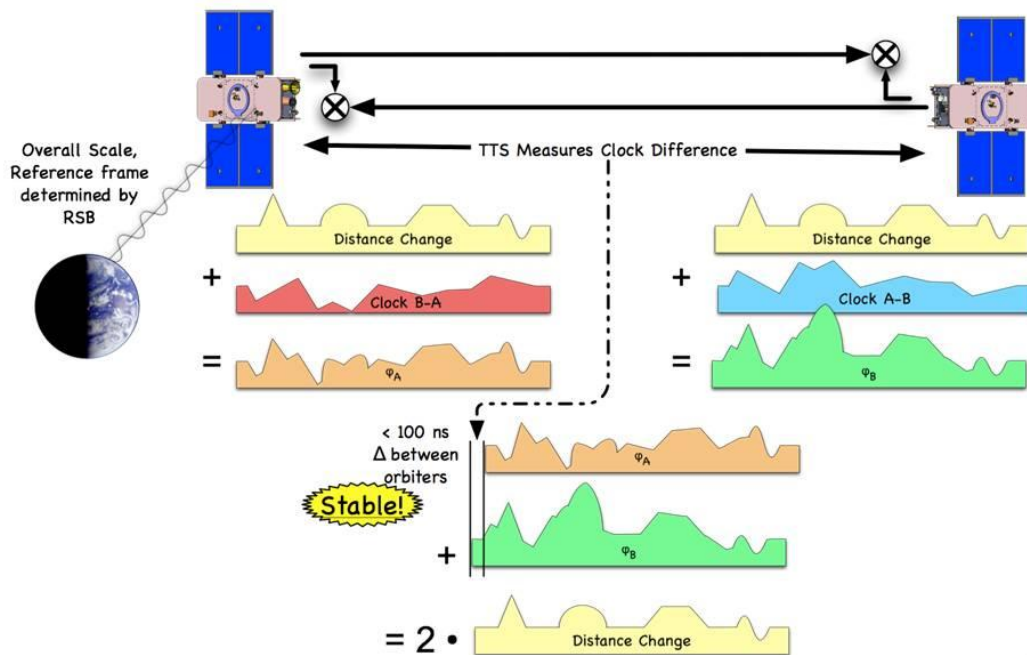


This document has been reviewed for export control and it does NOT contain controlled technical data

Measurement technique: Differential one-way ranging.



GRAIL payload function.



Project overview

Mission:

- Twin spacecraft launched on a Delta 2920H-10
- Launch in Sep. 2011
- Short duration of 9-months
- 82 day mapping mission
- Low altitude, polar orbit
- Single payload mission
- Imaging for education program

Measurements:

- Ka-band ranging measures relative velocity of the centers of mass of two spacecraft
- Links to Deep Space Network for navigation, absolute position, and timing calibration



Institutions:

- **MIT:**
 - Principal Investigator & Deputy
 - Science analysis & interpretation
- **JPL:**
 - Project management, system engineering, mission assurance, mission operations, payload development, science simulations & modeling, data processing
 - Contract with Lockheed Martin for spacecraft system
- **LM:**
 - Spacecraft development & flight operations
- **GSFC:**
 - Data processing & analysis
- **Sally Ride Science:**
 - Education & outreach cameras

Delta II 7920H-10 launch vehicle

• **Manufactured by ULA**

- Certified Category 3 LV
- 90 consecutive successful Delta II launches since Jan 1997

• **Approximately 124 feet tall and 8 feet in diameter**

• **First Stage:**

- Main engine (RS-27A) & nine (Ø 46") strap-on solid rocket motors
- LOX and RP-1 (kerosene), liftoff thrust of 207,000 lbs
- Each solid rocket motor produces 136,400 lbs. of thrust
- 3 Axis Stabilized

• **Second Stage:**

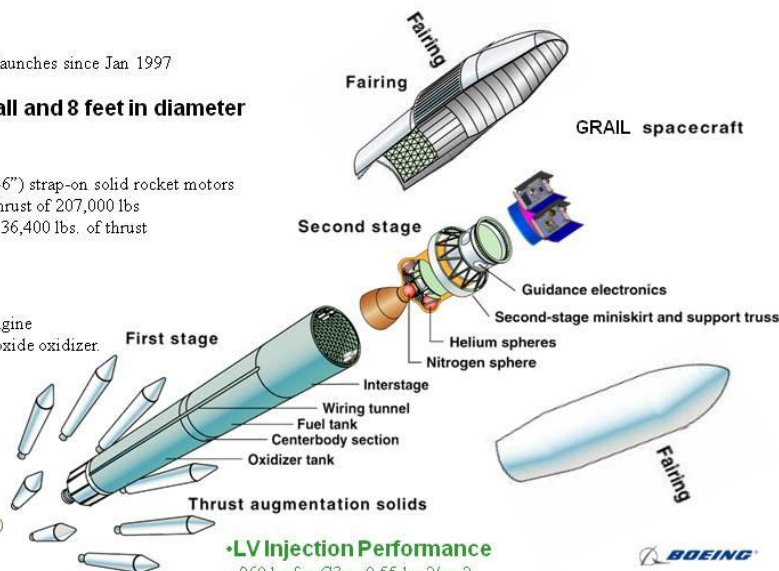
- Aerojet AJ10-118K second stage engine
- Burns Aerozine-50 & nitrogen tetroxide oxidizer.
- Vacuum-rated thrust: 9,645 lbs
- 3 Axis Stabilized

• **Payload Interface:**

- Standard 6915 PAF replaced with Direct Mate Adapter (DMA) & Spacer rings and Launch Vehicle Adapter Assembly (LVAA)

• **Launch Site:**

- SLC-17B
- Astrotech Commercial Integration Facility



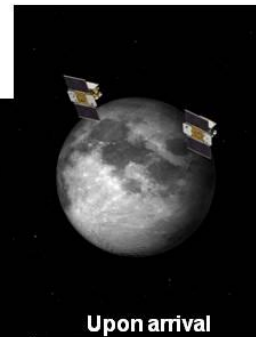
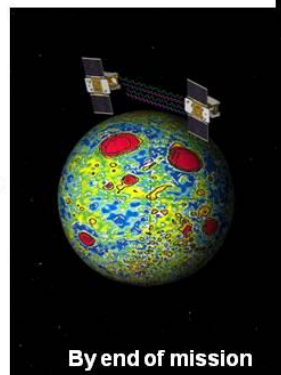
• **LV Injection Performance**

- 960 kg for C3 = -0.55 km²/sec²
- Includes interface rings & hardware above stage II
- 818 kg is GRAIL MPV and LV allocation

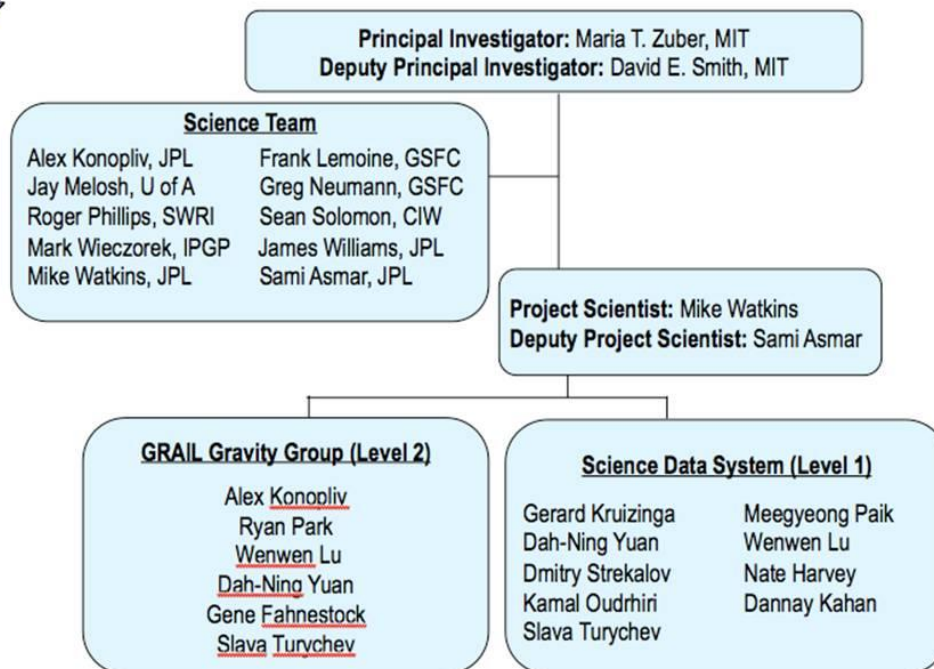
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Science team

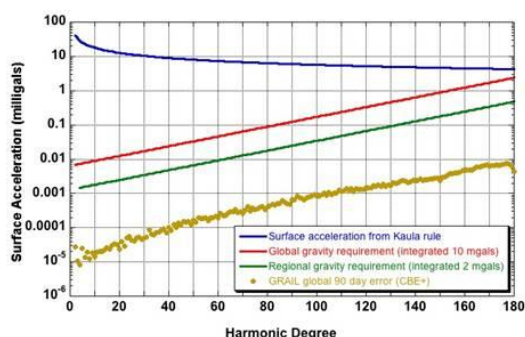
- **Maria T. Zuber** (MIT; PI)
- **David E. Smith** (MIT; DPI)
- **Michael M. Watkins** (JPL; PS)
- **Sami W. Asmar** (JPL; DPS)
- **Alexander S. Konopliv** (JPL)
- **Frank G. Lemoine** (GSFC)
- **H. Jay Melosh** (U. Arizona)
- **Gregory A. Neumann** (GSFC)
- **Roger J. Phillips** (SWRI)
- **Sean C. Solomon** (Carnegie Inst.)
- **Mark Wieczorek** (Univ. Paris)
- **James G. Williams** (JPL)



Organization chart



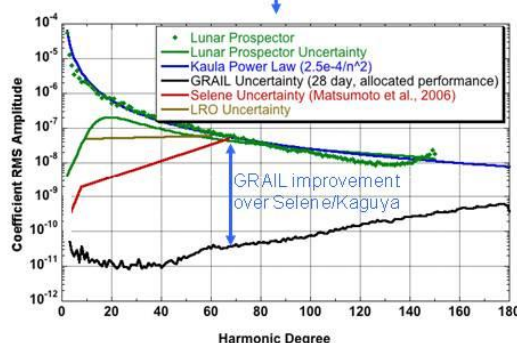
Summary of GRAIL Performance



- Significantly exceeds requirements for thermal and crustal studies.

- Meets requirements for interior and core.

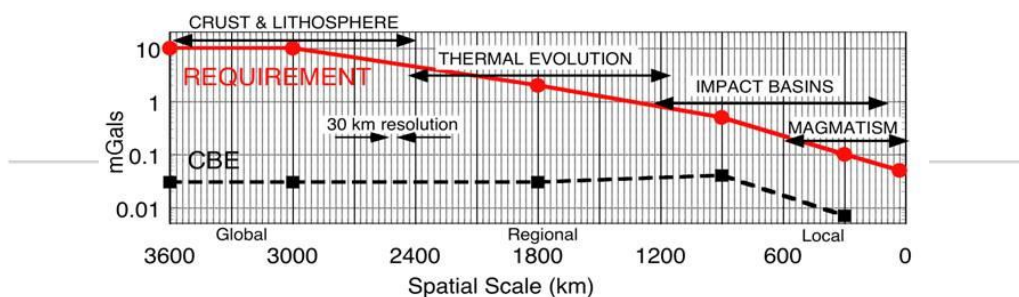
- Nearly 4 orders of magnitude better than Lunar Prospector.
- Nearly 3 orders of magnitude better than LRO.
- Over 2 orders of magnitude better than SELENE/KAGUYA.



→ GRAIL is a capability-driven mission.

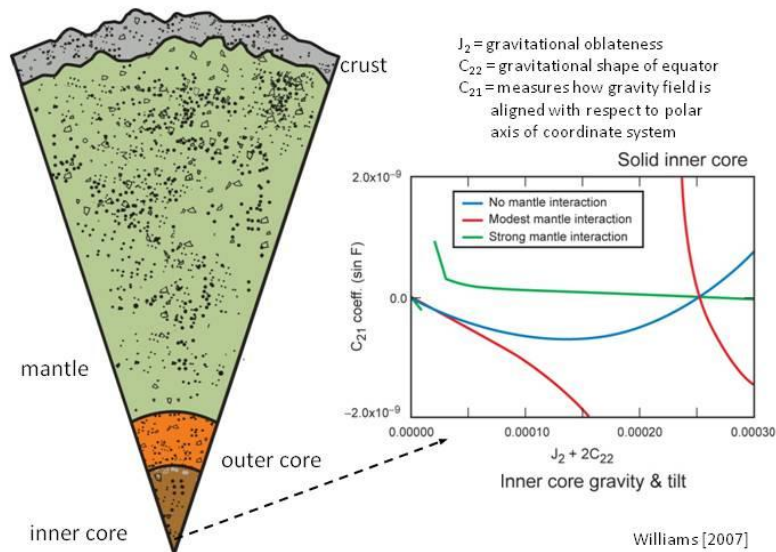
Baseline science requirements: Investigations 1-4

Science Investigations	Area (10 ⁶ km ²)	Resolution (km)	Requirements (30 km block)	Current Best Estimate 90 days
1. Crust & Lithosphere	~10	30	± 10 mGals, acc.	± 0.03 mGals
2. Thermal Evolution	~4	30	± 2 mGals, acc.	± 0.03 mGals
3. Impact Basins	~1	30	± 0.5 mGals, prec.	± 0.04 mGals
4. Magmatism	~0.1	30	± 0.1 mGals, prec.	± 0.007 mGals



→ CBE performance considerably exceeds requirements for each of Science Investigations 1 through 4

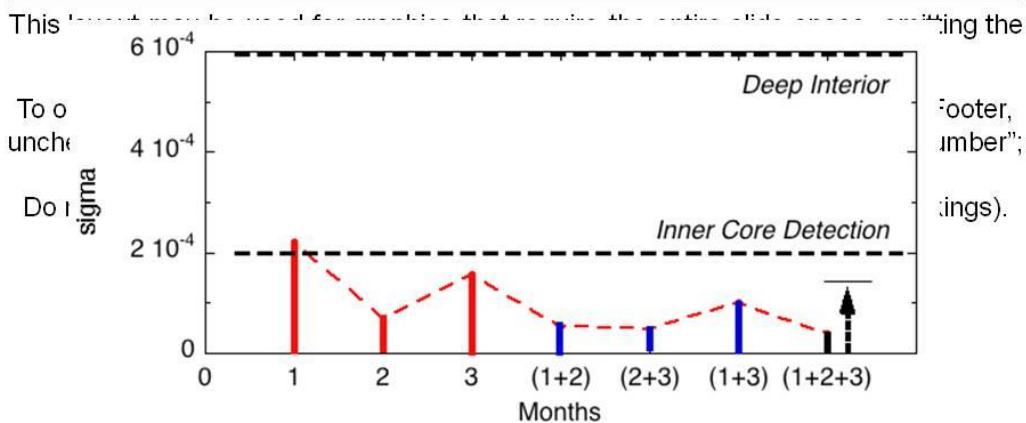
Deep interior: Inner core detection



Trade-off between inner core gravity and tilt required to detect solid inner core

Investigation 5 and 6

Science Investigations	Area (10^6 km^2)	Resolution (km)	Requirements (30 km block)	Current Best Estimate 90 days
5. Deep Interior	N/A	N/A	$k_2 \pm 6 \times 10^{-4}$ (3%)	$\pm 1.4 \times 10^{-4}$
6. Inner Core Detection	N/A	N/A	$k_2 \pm 2 \times 10^{-4}$ (1%)	$\pm 1.4 \times 10^{-4}$



→ CBE performance meets requirement for deep interior and inner core detection.

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Key Assumptions for Investigation 5 and 6

Cases 2009 CDR Initial Conditions	K2 error	C21 error	S21 error
2 hour batch, 3E-12 km/s² (1 day AMD)	1.681e-04	1.202e-10	4.621e-11
2 hour batch, 3E-12 km/s² (2 day AMD)	1.307e-04	9.564e-11	3.541e-11
2 hour batch, 3E-12 km/s² (3 day AMD)	5.174e-05	4.066e-11	1.971e-11
2 hour batch, 1E-12 km/s² (2 day AMD)	1.082e-04	7.619e-11	1.792e-11
2 hour batch, 5E-13 km/s² (2 day AMD)	9.502e-05	6.650e-11	1.405e-11
2 hour batch, 1E-13 km/s² (2 day AMD)	5.542e-05	4.005e-11	1.084e-11
Requirements	2.2e-04	1.0e-10	2.5e-11

"More Conservative"

"CDR Baseline"



"Less Conservative"

- AMD Frequency Baseline in 2-4 days, worst case is 1 day
 - Stochastic acceleration experience from other missions range from 1 to 10E-13 km/s², baseline conservatively chosen as 3E-12
- => "Baseline assumptions are conservative and range of values significantly improves margins"



Views of our spacecraft and Payload

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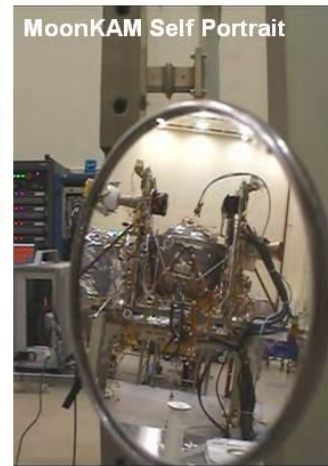
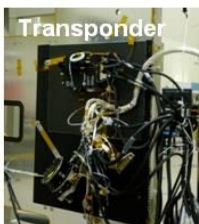
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ATLO highlights



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Science Planning and Implementation

Science planning

- GRAIL is a single-instrument mission.
- GRAIL payload has a single mode of operations and one data type.
- A second data type is Doppler tracking acquired at DSN (LOS).
- GRAIL is a polar orbiter mapper and has no “targeting”.
- Sensitivity to different science objectives built into mission design.
- **Non Applicable:** science planning process and science team prioritization typical for multiple instruments or multiple targets as well as time-sequenced events.
- Members of the science team with varying research objectives process and interpret the data differently from one another, but the data observables are common.
- Members of the science community eventually access data archived at PDS and utilize the same data observables.
- MoonKam images acquired for E/PO on best efforts basis.

Science planning & modeling

- The GRAIL version of **Science Planning** is a series of modeling and simulation activities.
- Examine all possible contributors to errors in gravity recovery.
- Set up required tools for Level 1 and Level 2 processing.
- Conduct peer reviews to validate all formulations.
- Provide feedback to spacecraft team (in design phase).
- Decide DSN acquisition strategies for optimizes science.
- Test all interfaces.
- Document entire process.

Science implementation

- GRAIL science team works closely with:
 - Mission Planning & Navigation
 - Spacecraft system contractor (LM)
 - Payload developer (JPL)
 - Deep Space Network
 - Science staff (Science Data System & GRAIL Gravity Group)
 - Planetary Data System
- to implement the science plan and optimize the scientific measurements.
- **Software:** specialized tools for gravity recovery
 - Primary tool is MIRAGE, a version of the JPL Orbit Determination Program (ODP) designed especially for spacecraft-to-spacecraft links and fully validated for GRACE and numerous missions over decades.
 - Secondary tool is GEODYN, a GSFC orbit determination and gravity modeling software system that provides some different capabilities as well as independent verification.

Science implementation: Role of mission design

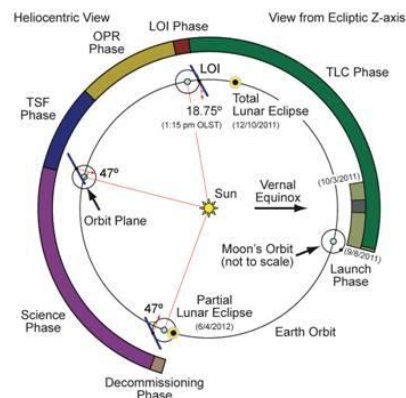
- The sensitivity to science investigations (local vs. regional vs. global) accomplished by varying spacecraft altitude and separation
- Start low and close, move high and far, return to low and close
- Lower orbit increases sensitivity to shorter wavelength (surface features ~30 km)
- Higher orbit increases sensitivity to longer wavelength (global/core)
- Used to be in three “cycles” but moved away from that terminology



Mission phases

GRAIL	2011					2012						
	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	
<div>Critical Events</div>		<div>Launch</div>				<div>LOI-A</div>						
Mission Phase	<div>Launch</div>	<div>Trans-Lunar Cruise</div>				<div>LOI</div>	<div>OPR</div>	<div>TSF</div>	<div>Science</div>			<div>Decommissioning</div>
	<div>9/8</div>	<div>Launch Period</div>	<div>10/3</div>			<div>12/28</div>	<div>1/2</div>	<div>2/6</div>	<div>3/6</div>		<div>5/31</div>	<div>6/4</div>
					<div>12/10</div>				<div>Mapping Cycle 1</div>	<div>Mapping Cycle 2</div>	<div>Mapping Cycle 3</div>	<div>6/4</div>
					<div>Total Lunar Eclipse</div>							<div>Partial Lunar Eclipse</div>

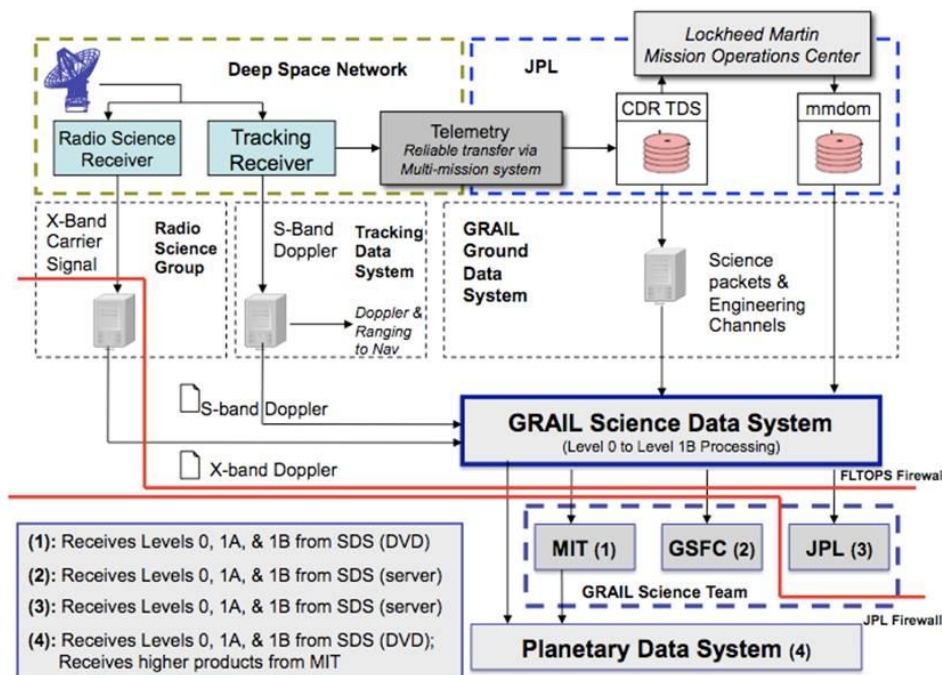
- 1) Launch Phase
- 2) Trans-Lunar Cruise (TLC) Phase
- 3) Lunar Orbit Insertion (LOI) Phase
- 4) Orbit Period Reduction (OPR) Phase
- 5) Transition to Science Formation (TSF) Phase
- 6) Science Phase
- 7) Decommissioning Phase



Nominal end-to-end science plan

- Nominal science phase begins after orbit insertion and transfer to science formation (TSF).
- Payload antennas pointed to each other and science data are acquired for 82 days.
 - Ultra-Stable Oscillator (USO) powered shortly after launch to reach optimum stability and its drift monitored in cruise phase.
- When the two spacecraft are in view of Earth (not occulted by Moon), downlink telemetry payload data to DSN and X-band Doppler is acquired on a separate stable link to DSN .
 - Nominal DSN tracking: 8 hour per day per spacecraft
- Payload data and Doppler data are delivered to a Science Data System (SDS) for processing.
- Mission ends due to solar eclipse on spacecraft panels.

GRAIL science data flow

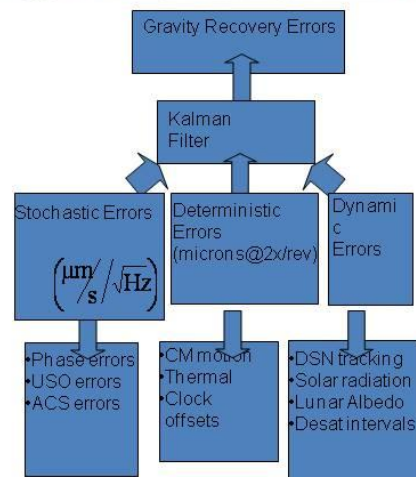


Nominal plan: Data types and levels

- Level 0: **dual one-way phase**
 - Acquired by instrument as well as DSN Tracking data
- Level 1: **instantaneous range-rate**
 - Processed by SDS
- Level 2: **Gravity field**
 - Processed by MIRAGE (JPL Orbit Determination Program)
- Analysis includes very large number of errors with complex spectral content - run on JPL supercomputers
- Two (of three) successful **Peer Reviews** held on algorithms and data processing with world experts in the field

Gravity recovery errors

- **Mission Characteristics**
 - Altitude & Separation
- **Dynamics**
 - Surface Forces
 - Generic Periodic Acceleration
 - Lunar Albedo and thermal emission
 - Angular momentum maneuvers
 - Lunar Libration
 - Omission/Commission of mean field
 - Status of out-gassing
- **Kinematics:**
 - DSN/KBR time tag offset
 - Attitude control errors
 - Thermal variations (tone errors)
- **Instrument noise**
 - Quality of USO
 - Choice of X-band vs. S-band
- **DSN Coverage**
- **Processing**



- Gravity recovery from spacecraft tracking is highly amenable to Kalman filter based simulation and covariance analysis
- Long and deep history and mature software - used for GRACE, Cassini, MRO, etc.

Off-nominal operational scenarios

- Early choices were made to lower the cost but maintain the highest possible reliability.
- High confidence due to short mission.
 - Single string payload components (on each spacecraft)
- Project team initiated study of off-nominal scenarios
- Example questions in trade space:
 - Is flyby with later LOI attempt feasible?
 - Do we have enough delta-V to attempt it?
 - Can the other orbiter survive long enough?
 - Is downlink-only science feasible?
 - Is S-band only science feasible?
- The impact of each question (longer list) on each of six science objectives is being assessed.

Archiving

- All documents and gate products governing science management, data management, archiving, and all relevant interfaces are in place.
 - **Science Management Plan**
 - **Science Data Management Plan**
- Project is prepared to meet all obligations to archive all required data.
 - All interfaces to Planetary Data System are in place
 - High heritage; no new products
 - Experienced team with archiving Radio Science data
 - Will schedule a PDS peer review in the near future.

Principal Investigator closing comments: Attributes for success



NASA/JPL/Galileo

- Early definition of requirements.
- Early identification of and investment in risk items.
- Open communication and strong support among mission/science team, NASA HQ and Discovery Program office.
- Flexibility in definition or at least interpretation of success criteria.



Contents

- Overview of Mission
- Overview of Science
- Science Planning and Operations Implementation
- Data Archiving
- Replan Process/Transition Criteria



Mission Overview



Wilhelm Olbers Discovers Vesta in 1807



4



Dawn History 1



- 1992 Discovery Workshop, San Clemente, California
 - C.T.R. meets Mark Hickman, NASA Lewis ion engine salesman
 - Ion engine science mission study team formed
- 1994 Proposal submitted for Diana mission to Moon and an active asteroid. Not selected. Lunar Prospector and Stardust selected.
- 1996 Proposal submitted for Comet Tempel 2 Rendezvous and Main Belt Asteroid Rendezvous [Vesta, Lutetia, Glaserappia]. Neither selected. Contour and Genesis selected.
- 1998 Proposal submitted for Main Belt Asteroid Rendezvous [Vesta, Lutetia]. Not selected. MESSENGER and Deep Impact selected.
- 2000 Proposal submitted for Dawn, mission to Vesta and Ceres. First time these two targets accessible on single mission. Selected for Concept Study.

Discovery Program Workshop

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Dawn History 2



- 2001 Concept study begun. Step 2 proposal submitted in summer. Site visit scheduled for September 12 in DC area. Canceled on 9/11. LA-area Dawn team crosses country in 4 vehicles in 48 hours. Site visit rescheduled. Successful. Dawn selected with Kepler.
- 2002 Delayed start because of funding issues. New launch date and larger rocket needed. Inexperienced team gets slow start. Lose laser altimeter to large cost escalation. Descope height resolution to 10m. Shorten Vesta encounter with loss of second high-altitude mapping. PDR in Fall seems to be successful. Mission canceled Christmas Eve.
- 2003 MER lands successfully. Orbital protests cancellation. Dawn reinstated at cost of magnetometer.

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Dawn History 3



- 2004 Dawn enters phase C and proceeds successfully into development.
- 2005 Dawn asks for a small increase in budget in September. In October, NASA requests standdown during which HQ investigates the project.
- 2006 Standdown continues past the time of congressional budget hearings. As soon as hearings end, Dawn is canceled. JPL appeals on basis that agreed-upon procedures were not followed. JPL wins.
- 2007 Dawn assembled, tested, and shipped off to Cape for July launch. This is the second last opportunity before Ceres moves out of position. An afternoon launch in July is almost impossible. Boat and plane needed for mid-Atlantic telemetry both have trouble. Fortunately, second stage does not get fueled or there would be no mission today. Launch rescheduled to September. Finally a beautiful launch on September 27.

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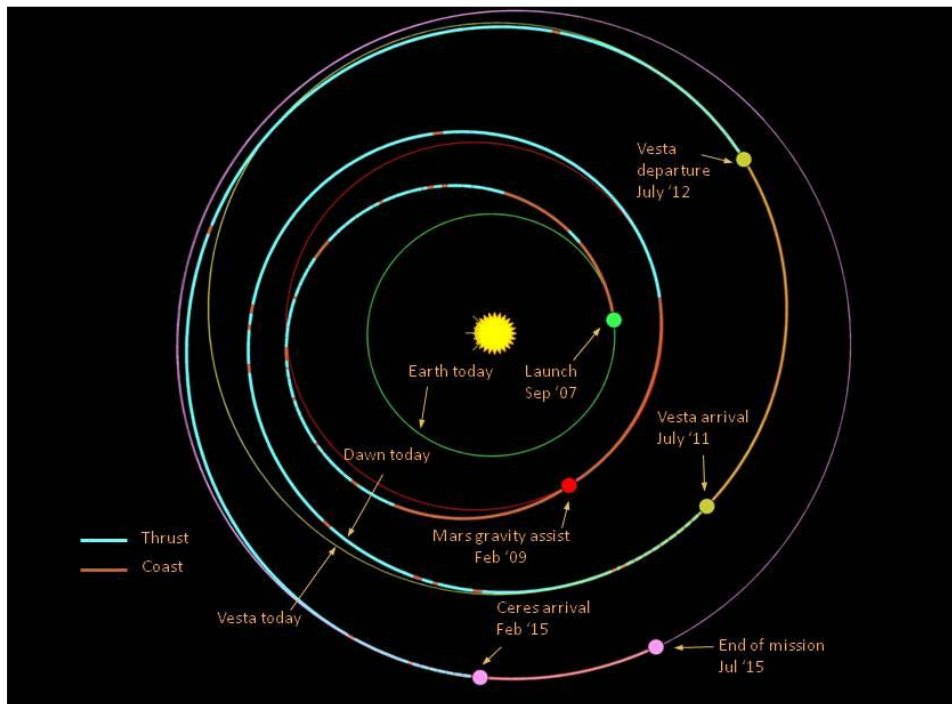
Dawn Launch



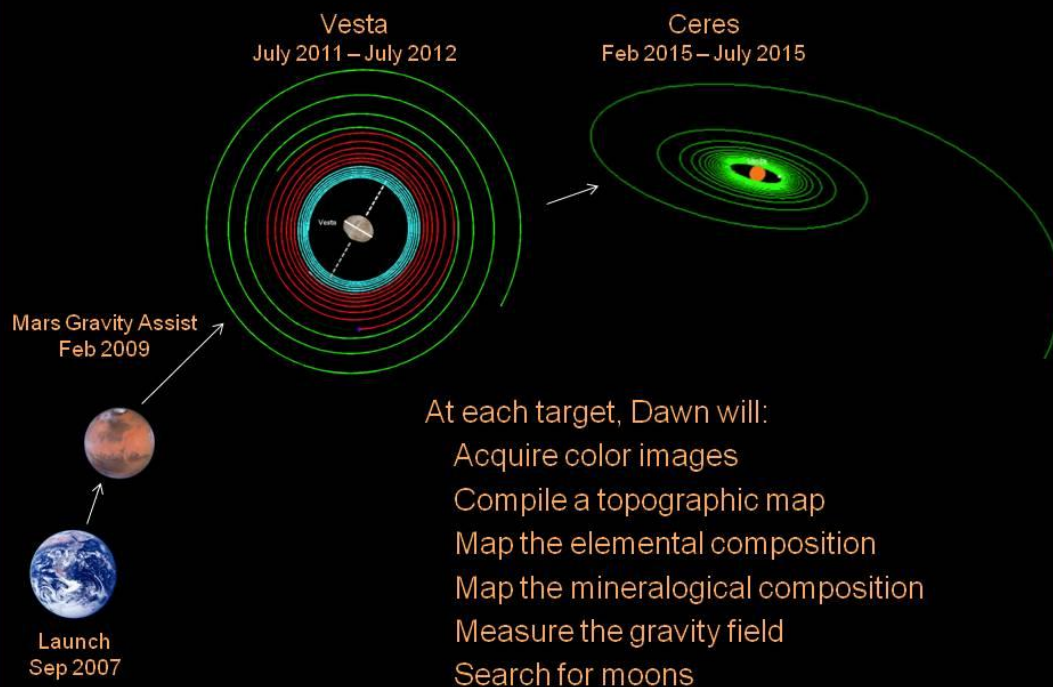
Photographs copyright Randy Pollock (2007) Sticking copyright Johan Kviniemi (2007)



Interplanetary Trajectory

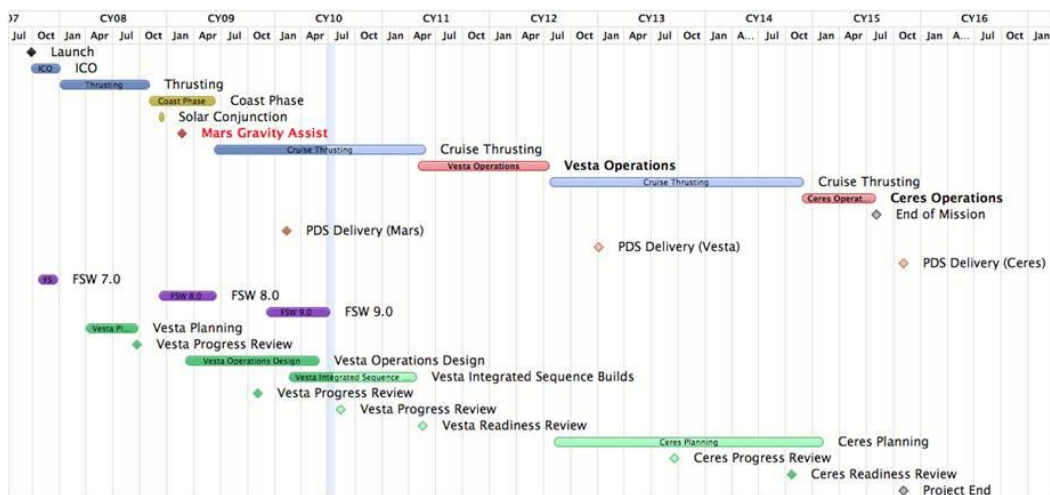


Dawn Mission Itinerary





Long-Range Project Schedule

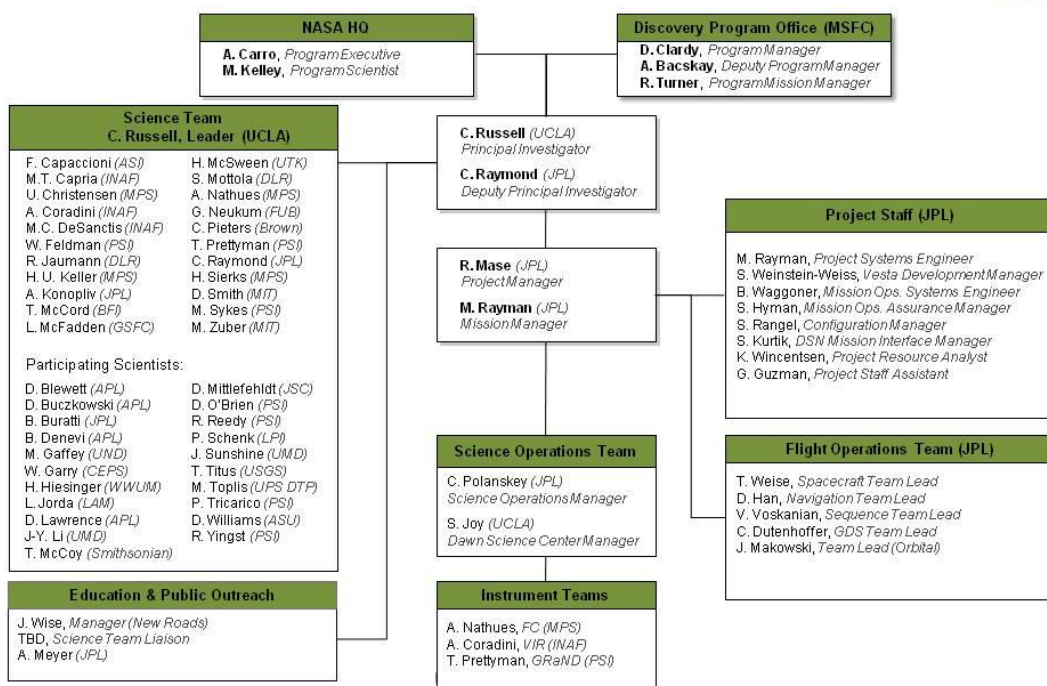


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Dawn Project Organization





Science Overview

Dawn will characterize the surfaces of two complementary protoplanets, Vesta and Ceres, and probe their internal structure

- ✧ **Map the geologic units**
- ✧ **Create detailed shape models**
- ✧ **Determine how and when the bodies formed**
- ✧ **Understand the internal and external forces that shaped them**

Dawn uses ion propulsion to explore the main asteroid belt

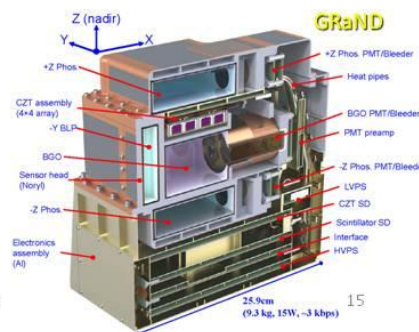
- ✧ **425 kg of xenon imparts a Δv of 11 km/s**
- ✧ **IPS operates for > 50000 hrs during mission**

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Dawn's Payload

- Two redundant framing cameras (1024 x 1024 pixels, and 7 color filters plus clear) provided by Germany (MPS and DLR)
- A visible and infrared mapping spectrometer (UV to 5 microns) provided by Italy (INAF and ASI)
- A Gamma Ray and Neutron Detector built by LANL and operated by PSI
- A Radio Science Package provides gravity information
- Topographic model derived from off-nadir imaging



Discovery Program Workshop



L-I Science Requirements Compliance



Vesta Level 1 Science Requirement	Principal Orbit	Instrument System	Status
Determine the bulk density to 1%	Survey	GRV,FC	Comply
Determine the Spin axis to 0.5 deg	Survey	FC	Comply
Obtain images of 80% of the surface with a resolution of 100 m/pixel in the clear filter and 3 color filters	HAMO	FC	Comply
Obtain a topographic map of 80% of the surface, with horizontal resolution of 100m, and vertical resolution of 10 m	HAMO	FC	Comply
Obtain 10,000 spectral frames at wavelengths of 0.25 – 5 μm with a spectral resolution of 10 nm (to measure and map the mineral composition). At least half of these spectral frames will be at a spatial resolution ≤ 200 m, with the rest at a spatial resolution ≤ 800 m.	Survey, HAMO	VIR	Comply
Measure and map the abundances of the major rock forming elements to 20% precision with a resolution ~ 1.5 times the mapping altitude over the entire surface to $\sim 1\text{m}$ depth	LAMO	GRaND	Comply
Measure and map the abundances of H, K, Th, and U over the entire surface to ~ 1 meter depth	LAMO	GRaND	Comply
Determine the gravity field with a half-wavelength resolution of 90 km	LAMO	GRV	Comply

Notes:

•These are not the formal statements of the success criteria

•The success criteria for Ceres are similar

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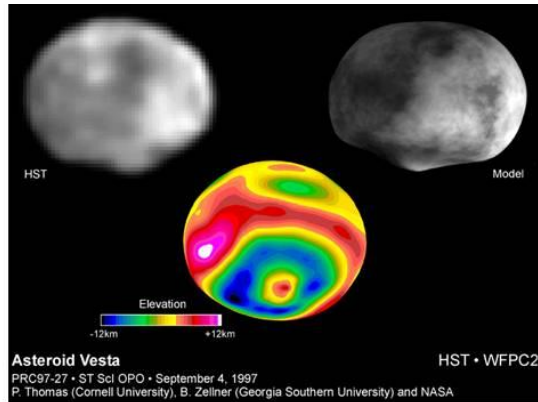
Dawn at Vesta (Jul '11- Jul '12)

Dawn will map the geology and composition of Vesta and measure its topography and gravity

- Composition, lithology and weathering with VIR (1.0 to 5.0 μm) and FC color filters
- Cratering history (FC)
- Elemental abundances from GRaND
- Topography, crustal thickness and density distribution

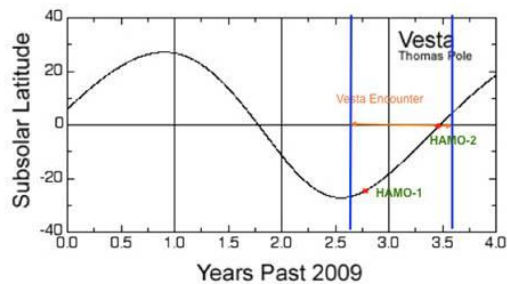
Northern polar region will be dark when Dawn arrives

- mapping the northern polar region will be accomplished late in the rendezvous



Diameter: 519 km

Density: 3700 kg/m³

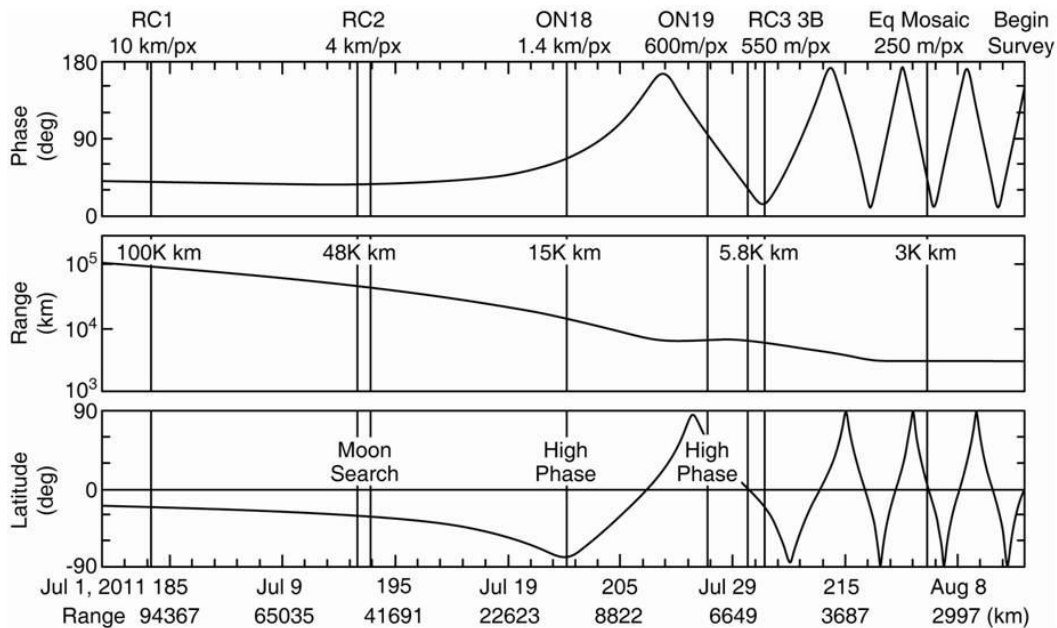


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Late Approach Phase



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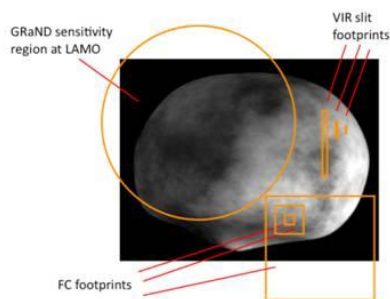
18



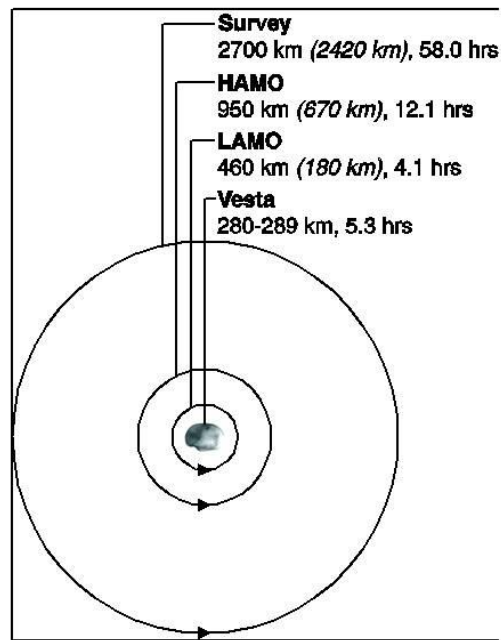
Vesta Science Orbits



- Dawn will begin taking data in a high *Survey* orbit
- It will then use the ion propulsion system to transfer two times to lower orbits
 - *High Altitude Mapping Orbit (HAMO)*
 - *Low-Altitude Mapping Orbit (LAMO)*
- Dawn then raises its orbit to perform a second HAMO, departs from Vesta, and repeats the same orbit strategy at Ceres



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Vesta Science Plan



- Approach
 - Rotational Characterizations with FC at decreasing range
 - VIR scan image cubes and FC mosaics to test integration times
 - Vesta satellite search of ~5000 km radius around body
- Survey
 - VIR global coverage @ ~600m resolution using pushbroom imaging and scan-mirror image cubes
 - Multiple FC mosaics with full rotational phase coverage @ ~270 m resolution
- HAMO
 - Two nadir FC global mappings in clear and 7 filters @ ~70m resolution
 - Four off-nadir FC global mappings in clear filter for topography
 - VIR 32-slit scan image cubes in northern hemisphere
 - VIR pushbroom acquisition in southern hemisphere (<200m res.)
- LAMO
 - 70 days of GRaND nadir observations @ 80% duty cycle
 - Global tracking coverage for gravity mapping a < 30 km equatorial spacing
 - Near-global FC imaging in clear and selected filters at ~20m resolution
- HAMO-2
 - One FC nadir mapping w/filters and three off-nadir clear mappings

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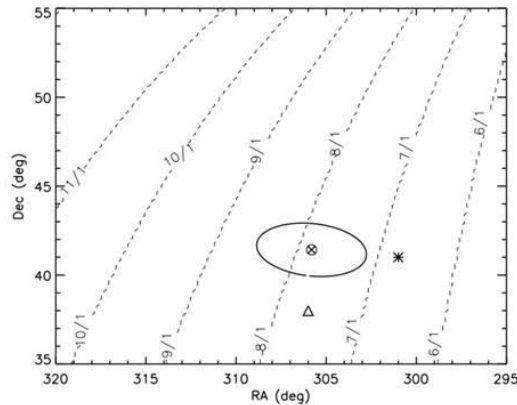
20



When Can Dawn Leave Vesta for Ceres?



- With the new observations, we obtain a more accurate pole position
 - Star gives the old Thomas pole
 - Triangle is the old Drummond pole
 - Circled X is the new consensus solution with uncertainty ellipse
- Arcs are great circles from individual observing periods. Their intersections should be at the pole position
- Background contours give the vernal equinox date when the Sun crosses the equator and first illuminates the north pole.
- In the region of the most probable pole position, the vernal equinox occurs in mid-July to mid-August which would require Dawn to stay until that time to see the polar region. Stereo imaging requires even higher sun elevation angles.
- This possible need for a delayed departure would extend not only the stay time at Vesta, but may also delay the arrival at Ceres.

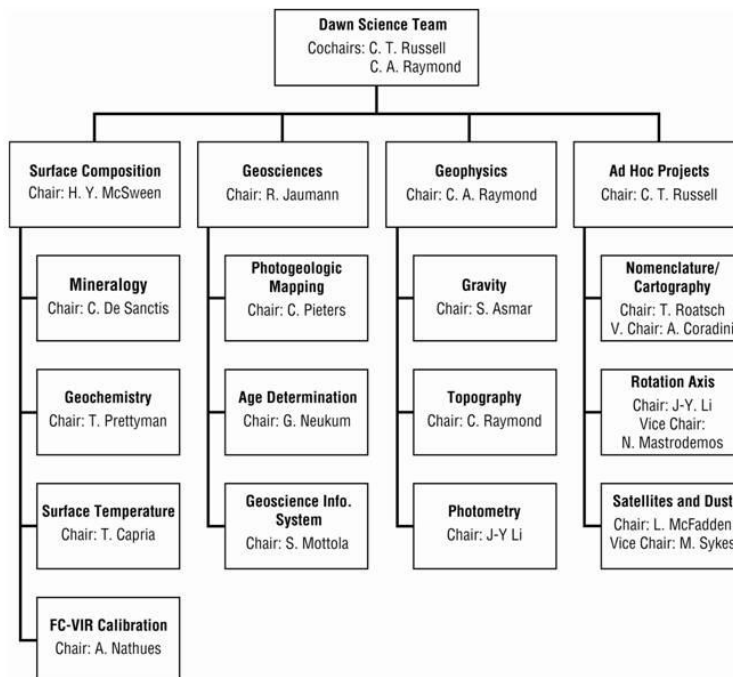


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Science Working Group Structure





Science Planning and Operations



Science Operations: Introduction



- The Dawn project follows the heritage, multi-mission uplink process shared by missions such as Mars Global Surveyor, Mars Odyssey, and Spitzer
 - Significantly different from larger projects such as Cassini, MER, MSL
- Dawn science operations are distributed between the Dawn Science Center (DSC) at UCLA and the Science Operations Support Team (SOST) at JPL
 - Teams are small so there is significant cross-training and back-up provided between teams
 - Key personnel have been with the project since development so there is continuity into operations
 - Processes and procedures have been developed and exercised during numerous cruise calibrations and instrument check-outs
- Dawn science planning philosophy is dominated by the uncertainty of the final orbit characteristics and the limitations of a small flight team
 - Sequencing strategy must be robust to changes in orbital characteristics
 - Sequences are modular and tied to geometric orbital events, not surface features, and not customized to a given trajectory
 - Limited targeted observations only late in each science phase



Major Challenges to Science Operations (and mitigations)



- Uncertainty in orbit characteristics and timing
 - Use relative-timed sequences tied to geometric epochs that allow the plan to sync up with the best predict (done)
 - Employ a late-update strategy to upload new ephemeris and epochs (done)
- Uncertainty in Vesta physical parameters
 - Reduce pole uncertainty (done)
 - Reduce plan sensitivity to the pole uncertainty (done)
 - Plan to update exposures with evolving photometric model (done)
- Power Steering (solar arrays always pointed to the Sun)
 - Utilized the VIR scan mirror to mitigate the slit co-linearity with s/c motion in northern latitudes (done)
- Attitude Control System Performance
 - Added new ACS fixed off-nadir pointing mode (Ahead/Across/Nadir) (done)



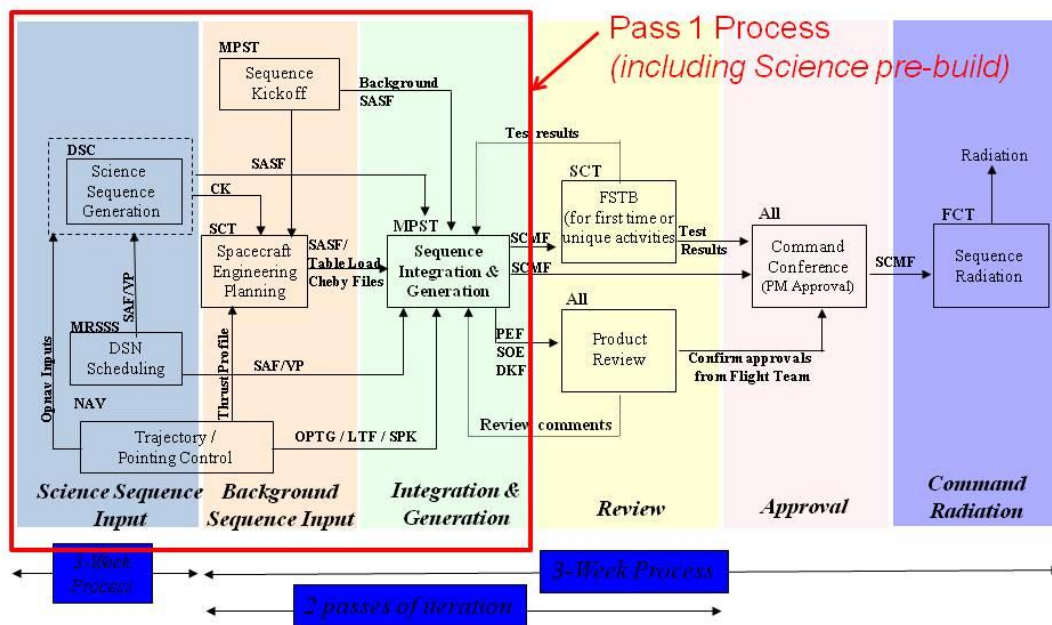
Major Challenges (cont.)



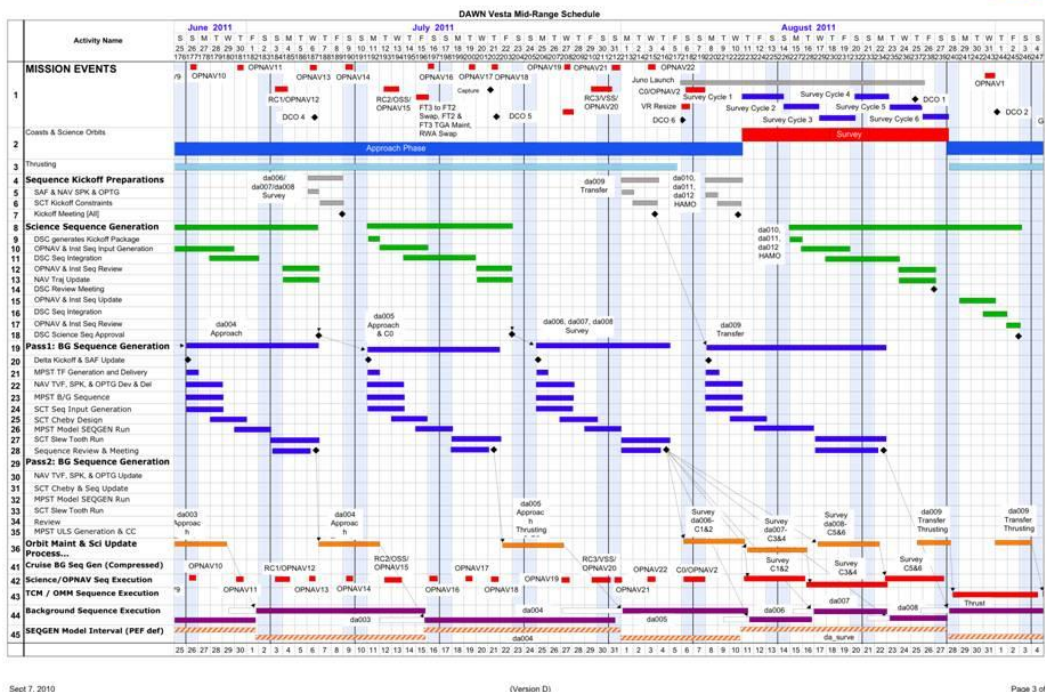
- Distributed international science team
 - German and Italian instrument teams with responsibility for building instrument sequences
 - One US science instrument
 - Developed good communication pathways, clear points of contact, site visits, and frequent face-to-face meetings
 - Developed detailed knowledge of our partners tools and software to make interfaces work smoothly
 - Involved science team in thread tests and operational readiness tests
 - Arranged for visiting Italian scientists to improve mutual understanding between the VIR team and the project



Sequence Development and Review Process



Example of Vesta Schedule



Sept 7, 2010

(Version D)

Page 3 of 9



Vesta Sequence Development Status



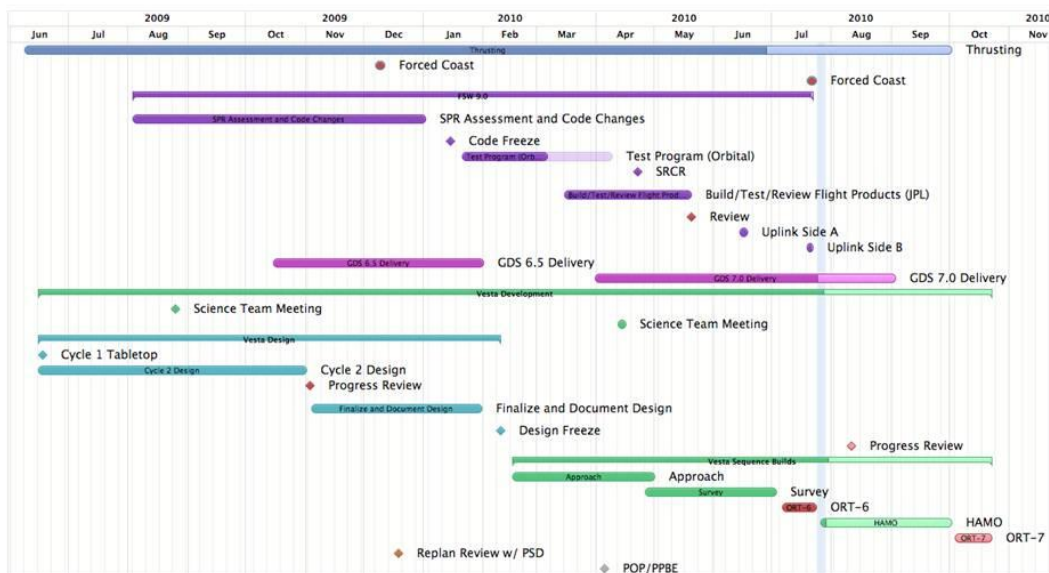
- Pre-Vesta Sequence Development started Feb 2010
 - Goal is to pre-build all Vesta sequences to the highest fidelity possible given the current knowledge of the orbits and s/c capabilities
 - All mission phases to be completed by end of cruise in April 2011
 - All spacecraft subsystems are required to participate
 - Strategies and observation plans are finalized
 - Liens and open items are documented
- DSC Update period begins one month before final sequence development starting in March 2011
 - Close approved liens from pre-build
 - Incorporate latest knowledge of body, trajectory, and DSN allocations
- Final sequence build and validation begins within 3-5 weeks of sequence execution
- Late updates are possible within 5 days of execution
 - Tweaks to onboard spacecraft ephemeris to improve pointing
 - Block shifts of sequence timing to line up with final trajectory phasing
 - Instrument exposures and integration time adjustments

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FY10 Project Schedule

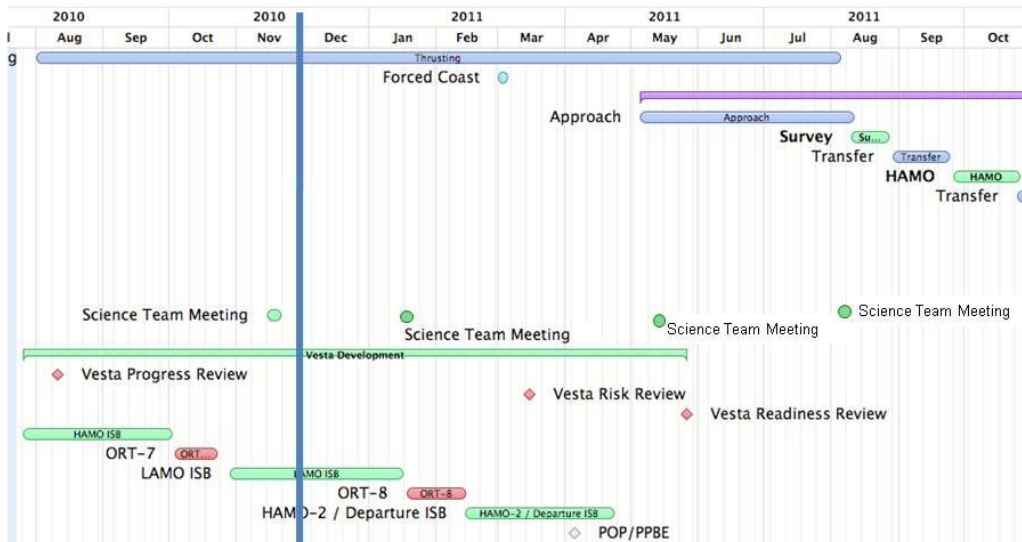


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FY11 Project Schedule



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Science Operations Support Team



- Located at JPL
 - Led by Dr. Carol Polanskey, Science Operations System Engineer
 - Robert Witoff, Science Opportunity Analyzer software engineer
- Provide science system engineering and science software development support to the Dawn Flight Team, the Dawn Science Center and the Dawn Instrument Teams.
 - Activity Lead/Flight Director for science activities
 - Support Science Plan and science strategy development
 - Develop and monitor science uplink schedules
 - Develop and maintain science operations processes/procedures
 - Monitor and review instrument uplink process development
 - Develop and maintain payload flight rules
 - Develop and maintain science block library
 - Develop and maintain payload contingency plans
 - Monitor and resolve instrument anomaly reports
 - Support instrument sequence testbed testing
 - Develop requirements and software support for science ground tools (Science Opportunity Analyzer (SOA) & Data Store Model)
 - Develop science operations training plan & monitor training certification

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Dawn Science Center



- Located at UCLA
 - Managed by Dr. Steven Joy
 - Joe Mafi, DSDb development and data archive
 - Xinping Liu, science planning & sequencing
 - Bridget Landry, science planning & sequencing (JPL)
- Provide science planning & sequencing and data archive support to the Dawn Flight Team and the Dawn Instrument Teams.
 - Support Science Plan and science strategy development
 - Develop activity-level description of the Science Plan
 - Receive, integrate, process and deliver instrument sequences
 - Produce science system-level and pointing sequences
 - Monitor and report on instrument health & safety status
 - Distribute instrument telemetry to the remote sites
 - Lead the Data Archive Working Group (interface to PDS)
 - Archive and review science data deliveries
 - Deliver final data products to the Science Team & Planetary Data System
 - Develop and maintain the Dawn Science Database (DSDb)
 - Project repository for science uplink & downlink products and documentation

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DSC Website



- The primary method of communication between the Science Team and the Dawn Science Center is the DSDb website
 - <http://dscws.igpp.ucla.edu> (dscws = DSC web server)
 - The website is password protected and requires a user account
- The DSDb provides access to documentation, meeting materials, sequence and planning products, and science data
- All Dawn data sets (raw, reduced) have been through the PDS peer review process and the formats have been finalized
 - Images in PDS and FITS format, GRaND in mostly ASCII tables
 - VIR in ISIS cube formats – with and without attached side plane (sp)

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Locating Data



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Institute of Geophysics and Planetary Physics
University of California, Los Angeles

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• Contact NASA

DAWN

About Dawn | Planning | Sequencing | **Data** | OpNav | SPICE | Documents | Status | Services | Edit | Logout (dsc)

This is the Dawn Science Database (DSDb) home page. The DSDb is used by the Dawn Science Team to communicate internally and with the Dawn Science Center.

Planning Science planning products and tools
Sequencing Instrument sequence development, upload, and retrieval tools
Data Data upload and download tools
OpNav Orbital navigation request, upload, and download tools
SPICE Access to PDS archive volumes
Documents Location of Dawn SPICE kernel files
Status Dawn science documents and presentations
Services Upload or review instrument status reports
 Miscellaneous DSDb services: user profile, duty roster, password changes, software downloads, bug reporting, feature requests, etc.
Help Site usage information

NASA Privacy Statement | Copyright | Feedback | Sitemap | System Requirements

FIRST GOV
The First DSDb to the U.S. Government

Curator: Steven Joy
Webmaster: NASA Official David Lindstrom
Last Updated: 1 Oct 2008
• Comments and Questions

From the home page, select **Data**

Then, on the Data page, select
Basic Data Search

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University of California, Los Angeles

DAWN

About Dawn | Planning | Sequencing | **Data** | OpNav | SPICE | Documents | Status | Services | Edit | Logout (dsc)

The data pages allow DSDb users to initiate real-time data flows to remote EGSEs, submit calibration, pointing, documentation) to the DSDb, and download existing products.

Overview
Realtime Telemetry
RT Connection Monitor
Basic Search
Advanced Search
PDS Archive Volumes

Realtime Telemetry
Initiate or terminate real-time data flows

RT Connection Monitor
Monitor realtime data flow connections

Basic Data Search
Explore DSDb data holdings

Advanced Data Search
Retrieve products from one or more datasets constrained on time, viewing geometry, lighting parameters.

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FIRST GOV
The First DSDb to the U.S. Government

Curator: Steven Joy
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• Comments and Questions

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Select Instrument



- First select an instrument – GRaND example

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DAWN

About Dawn | Planning | Sequencing | **Data** | OpNav | SPICE | Documents | Status | Services | Edit | Logout (dsc)

Level-1A: Raw Data

Location: [data](#) > [1a_edr](#)

type	author	cover date	size	actions
1a		2010-11-12	4,000 KB	
grand		2010-11-14	4,000 KB	
vtr		2010-11-12	4,000 KB	

Basic Search
Advanced Search
PDS Archive Volumes

Then select a data set, either "Quick Look" or "Latest Update". QL data are rapidly processed by using predict SPICE kernels. Latest Update contains data that the team has had a chance to review.
Select Latest Update

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DAWN

About Dawn | Planning | Sequencing | **Data** | OpNav | SPICE | Documents | Status | Services | Edit | Logout (dsc)

Data

Location: [data](#) > [1a_edr](#) > [grand](#)

type	file/directory	creation date	size	actions
Quick Look		2010-11-12	4,000 KB	
Latest Update		2010-11-12	4,000 KB	
GRaND_Data_Processing_v4.0.pdf		2010-11-14	7,701 MB	
GRaND_Operations_During_Cruise_v1.3.pdf		2010-11-14	352.0 KB	
MGA_Results_v1.1.pdf		2010-11-14	1,288 MB	
MVC_DC034_ActivityReport_v1.2.pdf		2010-11-14	276.8 KB	
MVC_DC041_ActivityReport_v2.0.pdf		2010-11-14	1,773 MB	

Basic Search
Advanced Search
PDS Archive Volumes



Data Organization



- Data are finally organized by the mission activity associated with the data acquisition. This proceeds from large scale phases (i.e. Cruise, Mars, Vesta), down to specific activities (Mars Closest Approach)

DAWN

[Edit](#) | [Logout](#) (dsc)

[About Dawn](#) | [Planning](#) | [Sequencing](#) | **Data** | [OpNav](#) | [SPICE](#) | [Documents](#) | [Status](#) | [Services](#)

[Overview](#)
[Realtime Telemetry](#)
[RT Connection Monitor](#)
[Basic Search](#)
[Advanced Search](#)
[PDS Archive Volumes](#)

Data

Location: [data](#) » [1a_edr](#) » [grand](#) » [latest update](#) » [mars](#) » [mga](#) » [dc023](#) » [09216_09218_GRAND_MARS_CA](#)

Bread crumbs

type	file/directory	creation date	size	actions
	LEVEL1A_AUX	2010-11-12	4.000 KB	
	LEVEL1A_GAMMA	2010-11-12	4.000 KB	
	LEVEL1A_NEUTRON	2010-11-12	12.00 KB	



Locating Documents



DAWN

[Edit](#) | [Logout](#) (dsc)

[About Dawn](#) | [Planning](#) | [Sequencing](#) | [Data](#) | [OpNav](#) | [SPICE](#) | **Documents** | [Status](#) | [Services](#)

This is the Dawn Science Database (DSDb) home page. The DSDb is used by the Dawn Science Team to communicate internally and with the Dawn Science Center.

[Planning](#) Science planning products and tools
[Sequencing](#) Instrument sequence development, upload, and retrieval tools
[Data](#) Data upload and download tools
[OpNav](#) Optical navigation request, upload, and download tools
[Archive](#) Access to PDS archive volumes
[SPICE](#) Location of Dawn SPICE kernel files
[Documents](#) Dawn science documents and presentations
[Status](#) Upload or review instrument status reports.
[Services](#) Miscellaneous DSDb services - user profile, duty roster, password changes, software downloads, bug reporting, feature requests, etc.
[Help](#) Site usage information

Begin by selecting *Documents* at the DSDb homepage

Documents are classified as:

Archive

Science Data Management Plan,
PDS Catalogs, Documents, etc.

Project

Science & Mission Plans,
Interface Agreements, etc.

Science Team

Telecon & Meeting presentations

DAWN

[Edit](#) | [Logout](#) (dsc)

[About Dawn](#) | [Planning](#) | [Sequencing](#) | [Data](#) | [OpNav](#) | **Documents** | [WG Wikis](#) | [Status](#) | [Services](#)

[Overview](#)
[Archiving](#)
[Project](#)
[Science Team](#)

Documents

[+ Add Document](#)

Location: [documents](#)

type	title	author	cover date	size	actions
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	Project		2009-06-30	4.000 KB	
	ScienceTeam		2010-11-12	4.000 KB	

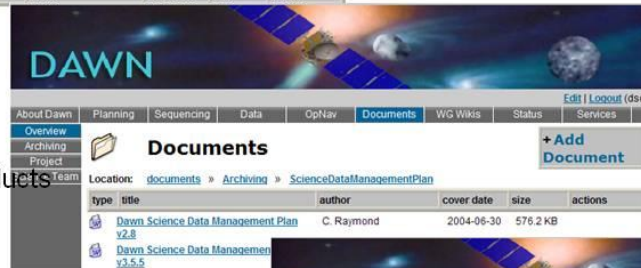


Example Documents



Operational Interface Agreements
(Defines key products and project delivery schedule agreements)

Science Data Management Plan
(Defines archive products and PDS delivery schedule)



Albuquerque Science Team Meeting Presentations
(Zip file creation in progress)



Instrument Operations Teams



- Instrument Teams are resident at their home institutions
 - JPL does not provide direct access to uplink or downlink tools
 - Pablo Gutierrez-Marques: FC Team (Max-Planck-Institut für Aeronomie) POC
 - Tom Prettyman: GRaND Team (Planetary Science Institute) POC
 - Sergio Fonte: VIR Team (Istituto Nazionale di Astrofisica) POC
- Provide instrument sequencing and data deliveries to the Dawn Science Center and the Dawn Science Team.
 - Support Science Plan and science strategy development
 - Develop internal uplink and downlink tools to meet project requirements
 - Produce and deliver instrument sequences
 - Support review of merged sequence products and testbed data
 - Perform trend analyses and monitor instrument consumables
 - Develop and maintain instrument calibrations
 - Support optical navigation requests (FC Team)
 - Monitor and report on instrument health & safety status
 - Report instrument anomalies
 - Deliver raw and processed science data products to the DSC

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Primary Interactions



- Science Team Telecons
 - Led by Carol Raymond
 - Weekly 1-hour telecons
 - Focus is on high level development of the Science Plan and definition of Science Team interactions
- DSC Tag-up
 - Lead by Carol Polansky/Steve Joy
 - Weekly 1-hour telecons
 - Focus is on details of instrument sequence development or fine tuning of operations processes
- Science Team Meetings
 - Twice or more per year
 - Alternate between US and European locations
 - Full Science Team interaction similar to the Project Science Group meetings for other projects

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Vesta Science Plan



- First iteration of the plan was released pre-launch
 - Initial release considered Vesta operations only
- Plan was fleshed out and evolved to current point
 - Working on Pre-Vesta Science Plan re-release
 - Will develop the Ceres Science Plan during Vesta-Ceres cruise
- Science Plan began with CSR and Level-1 requirements
 - Compiled by project science team (CAR, CAP, SPJ)
 - Reviewed by entire science team

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Science Planning Framework

- Dawn is a mapping mission planned to avoid resource contention
- Science Plan dictates which instrument controls the spacecraft attitude, and the distribution of data storage and downlink
 - Plan is proactive, not reactive
 - Some opportunities for targeted observations
 - VIR is prime in Survey orbit
 - FC also has dedicated activities
 - FC is prime in HAMO orbit
 - VIR “rides-along”
 - GRaND is prime in LAMO (80% duty cycle)
 - Dedicated gravity tracking occurs in LAMO
 - FC and VIR collect data opportunistically
- Plan is designed for robustness to loss of data
 - Functional (not actual) redundancy in collection of Level-1 data enhances the science return

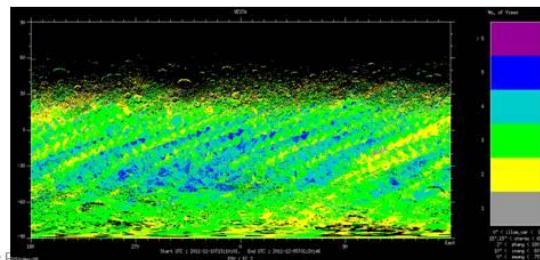
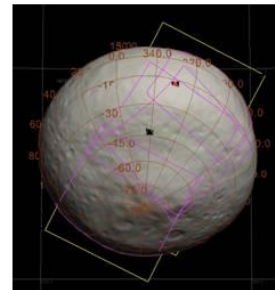
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Science Planning Tools

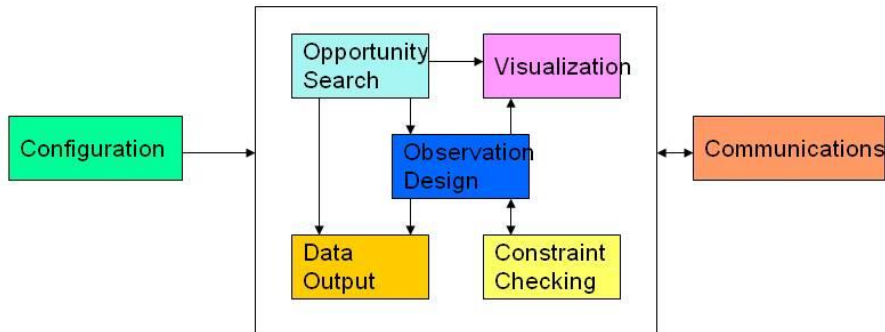
- Science Opportunity Analyzer
 - Multi-mission JPL tool
 - Developed for Cassini
 - Adapted for Dawn and Rosetta
 - Uses SPICE library
 - Java-based
 - Constraint checking and generates pointing kernels
- CK-View
 - DLR viewer developed Cassini
 - Adapted for Dawn
 - Uses SPICE library



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SOA Functions



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SOA Functions

- **Configuration**
 - Flight project adaptation is created by loading a project-specific configuration file
- **Opportunity Search**
 - Finds windows of opportunity for an observation based on specific geometric criteria
 - Provides 13 different searches with SOA core software using the Percy search engine supplied by the Navigation section
 - Cassini also provided EVENTS, a mission-specific Percy adaptation
 - Examples are eclipse, periapsis, occultation, ...
 - Supports construction of complex search criteria using AND, OR and NOT operators
 - Now available for all platforms

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SOA Functions



- **Observation Design**
 - Provides a high level “Scoping” design tool for “what if” studies
 - Supports nxm mosaic, continuous scan mosaic, roll about an axis, or track a target
- **Constraint Checking**
 - Check observations against specific geometric constraints
 - Provides easy to use flight rule builder
 - Allows user defined rules as well as project flight rules
- **Data Output**
 - Obtain ancillary data as either a tab-delimited text file or plots
 - Obtain data at any point along a trajectory with or without a specified spacecraft attitude
 - Provides results from models developed by the science community

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SOA Functions



- **Communications**
 - Interfaces to other components of the JPL legacy uplink system
 - Communicates with APGEN via interprocess communications
- **Visualization**
 - Provides accurate representation of the solar system in multiple ways
 - 3-D Arbitrary Observer: from an arbitrary point of view
 - 3-D Perspective Projection: from the viewpoint of the spacecraft
 - 2-D Equidistant Projection Skymap: Right Ascension/Declination map
 - 2-D Trajectory Plot: spacecraft trajectory plotted on either the x/y, x/z or y/z planes
 - Allows multiple views on one display or multiple viewer windows
 - Provides animation of the view over time

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Guiding Principles

- Science Plan development was guided by the following constraints:
 - Orbit prediction will be uncertain until very late in the sequence development process
 - Minimize observations targeted to specific features and focus on generic mapping
 - Schedule any targeted observations late in each mission phase
 - Link plan segments to geometric epochs that can be readily updated
 - Allow sufficient margin in turn times to handle extremes
 - Adopt a way-point pointing strategy to simplify operations and provide a means to get back on plan
 - Allow late update to ephemeris, epochs and pointing (if needed)
 - Flight system does not easily support data retransmission
 - Build functional redundancy into the acquisition plan
 - Create modular activity periods, “Cycles”, that can be repeated or re-ordered

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Science Plan Development

- Planning starts with coverage determination
 - **Science Opportunity Analyzer (SOA)** used to evaluate trajectory options and to determine the architecture of each orbit phase
 - Specific FC image separation or VIR frame repetition is determined to meet science objectives
- Engineering activities are inserted per requirements
 - OpNAV, orbit maintenance and engineering data playbacks
- Data flow and overall data volume are estimated using a spreadsheet model
- Coverage plan is adjusted to work within the data volume constraints
- Process is iterated with instrument teams until the plan fits within all required margins
- DSN playback times fall out of this analysis
 - Playback is initially planned for the dark portions of the orbit
 - Lit side playback is scheduled if all data buffers are full

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Approach Plan

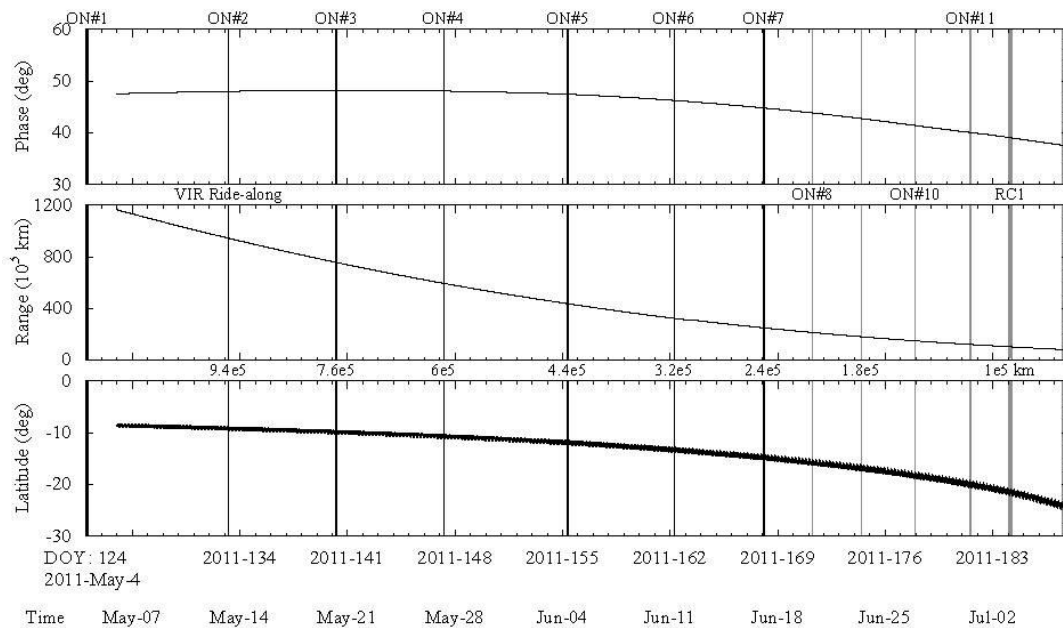
- Approach trajectory: AP2-001.bsp
- Time-ordered listing: SCItol:vsa_100203_AP2-001_SCItol_d.xls
- Plan includes activities requested for Approach phase:
 - Opnavs and associated VIR ride-alongs
 - Rotation Characterizations (RC) (with VIR ride-along)
 - Satellite (Moon) search
 - VIR Subsolar Observation
 - FC pre-Survey equatorial mosaic (C0)
- Plan assumes the following activities will be completed in the last pre-Approach forced coast period in March 2011:
 - VIR and FC Cals
 - FC1 checkout/cal
 - FC FSW Update (x2)
 - GRaND anneal
- Time-ordered listings for each activity and visualizations are included in backup

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Distant Approach – AP2-001



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Rotation Characterizations 1 & 2



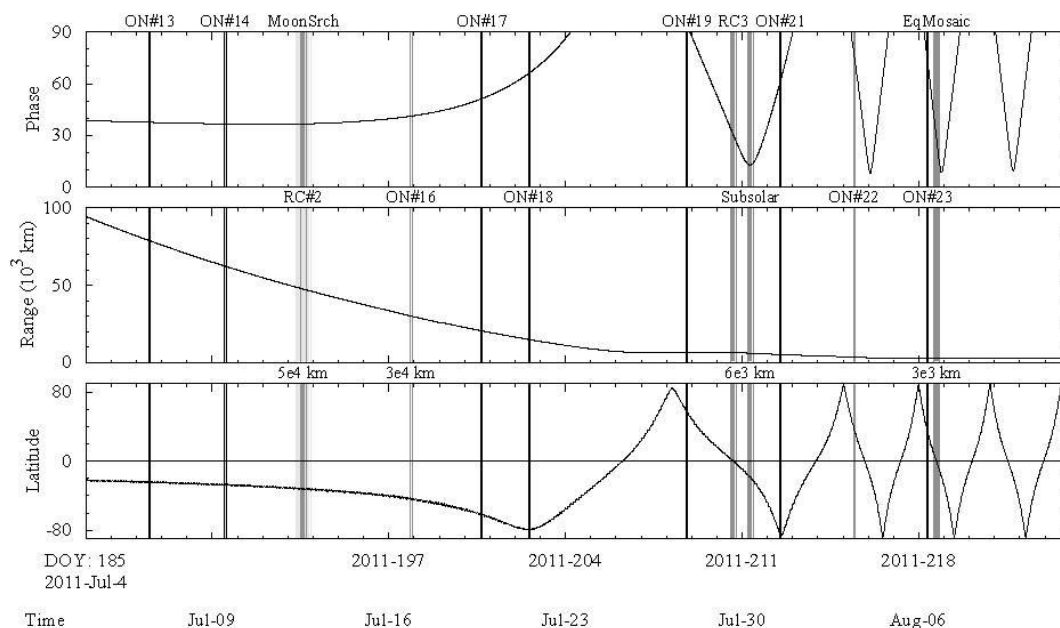
- **RC1 - Range dependent @100K range**
 - FC resolution is 10 km/px (Vesta = 50 px)
 - Take data during one rotation in all filters
 - Purpose is to test exposure times
 - Maximum range to resolve landmarks for Opanav
 - VIR resolution is 25 km/px (Vesta=20 px)
 - perform small scans using 32 steps around boresight
 - Purpose is to test integration times
- **RC2: Feed into trajectory update #4 (DCO = 35 days) and optimize southern latitude viewing**
 - FC resolution is 4.8 km/px (Vesta = 100 px)
 - Take data during one rotation in all filters
 - Purpose is to test exposure times and Opanav
 - VIR resolution is 12 km/px (Vesta=40 px)
 - perform small scans using 50 steps around boresight
 - Test 2-3 different integration times

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Near Approach – AP2-001a



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First Capture Orbit

- **RC3: dependent on latitude (equatorial) and phase angle (low)**
 - ~ 5000 km range: Vesta fills the FC FOV
 - FC rotation movie for gains and exposures with resolution close to Survey (~6 hr observation)
 - Critical Optrav activity
 - VIR ride along
- **VIR Subsolar observation: *Compromise between lowest phase and viewing of south pole***
 - Collect cubes of southern hemisphere (3 cubes, 1280 sec scan each)
 - Last chance to test integration times before sequence is final
 - Important Optrav observation

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Approach Summary

- Current plan includes activities to:
 - ensure full instrument calibrations and ties to ground-based observations
 - Improve knowledge of Vesta's pole and assess hazards to reduce risk in the plan
 - Unique observations to improve the Vesta photometry and derived phase function
 - May capture opposition surge at favorable slope geometry during pre-Survey CO mosaic
- **Integrated Sequence Build complete**
 - Sequences are on the shelf for update in mid-2011

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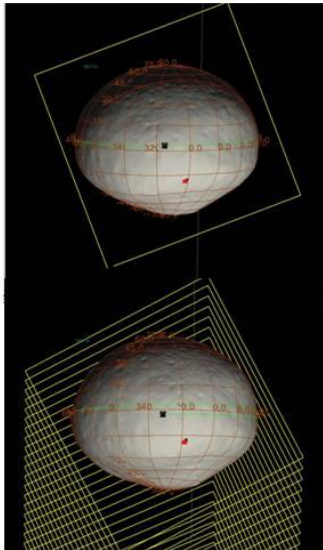


RC3 Plots



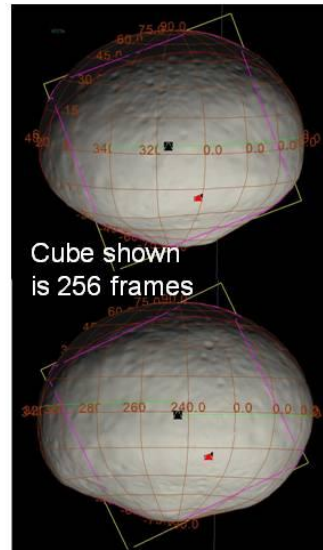
FC2/OpNav imaging
clear every 5m, filters every 20m
+04:00 to +09:20

3 VIS+IR cubes
(256 frame ea) every 1h10m
+04:00 to +09:20



Initial

Final



Cube shown
is 256 frames

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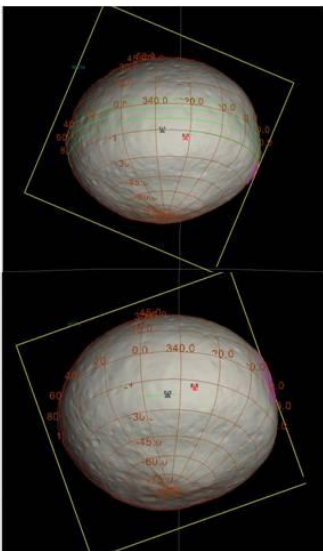


VIR Sub-solar Observation (RC3b) Plots



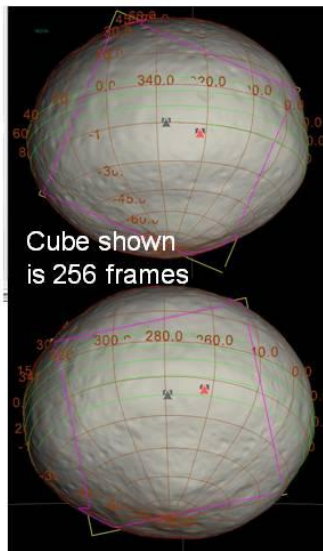
FC2/OpNav imaging
clear every 5m, filters every 20m
+19:50 to +25:10

6 VIS+IR cubes
(256 frame ea) every 55m
+19:50 to +25:10



Initial

Final



Cube shown
is 256 frames

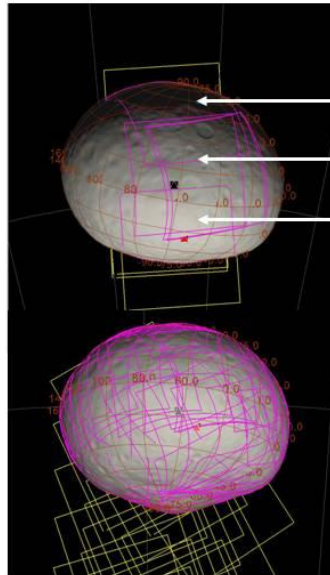
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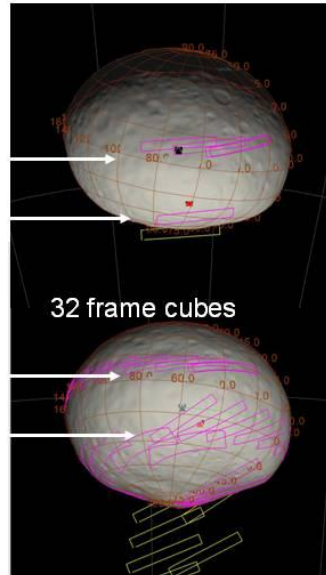
Orbit C0 - Plots



FC2 1x3 Mosaic



VIR ride-along



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Survey Plan



- Plan Overview
 - 6 orbit scenario
 - 6 Cycles of one orbit duration
 - Orbits 3 & 4 repeat the acquisition strategy of orbits 1 & 2, but observe new territory and fill in gaps
 - Orbits 5 & 6 collect new but functionally redundant data
 - Achieves low-spatial resolution portion of VIR requirement
 - Achieves the image mosaics needed to develop the shape model (part of Level-1 topography requirement)
 - Achieves the mapping goal to look at the entire lit body with optimal lighting conditions for VIR, and provide geologic context for later targeting imaging

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Survey Constraints and Requirements



- Constraints
 - Onboard memory (VR and Instrument)
 - Lighting conditions
 - Other activities (orbit maintenance; opnav imaging)
 - Begin with collection of Level-1 data with minimum complexity and build up
- Variables
 - VR sizes
 - Repetition time (# spectra per orbit) - 15sec is minimum rep rate that allows VIR to compress while sending data to the VR
 - Spectral and spatial resolution (# bits per orbit)
- Requirements:
 - Satisfy the Level-1 requirements of >5000 VIR spectra with high spectral/high spatial resolution (resolution of <800 m spatial res.), and spin axis to 0.5 degree
 - Obtain a complete global mapping of Vesta's shape and spectral variation to begin planning for later targeted imaging (nav and topo)
 - Allow sufficient time to confirm collection of Level-1 data and required nav data (prior to leaving Survey)
 - Allow development of targeted imaging plans for HAMO-2

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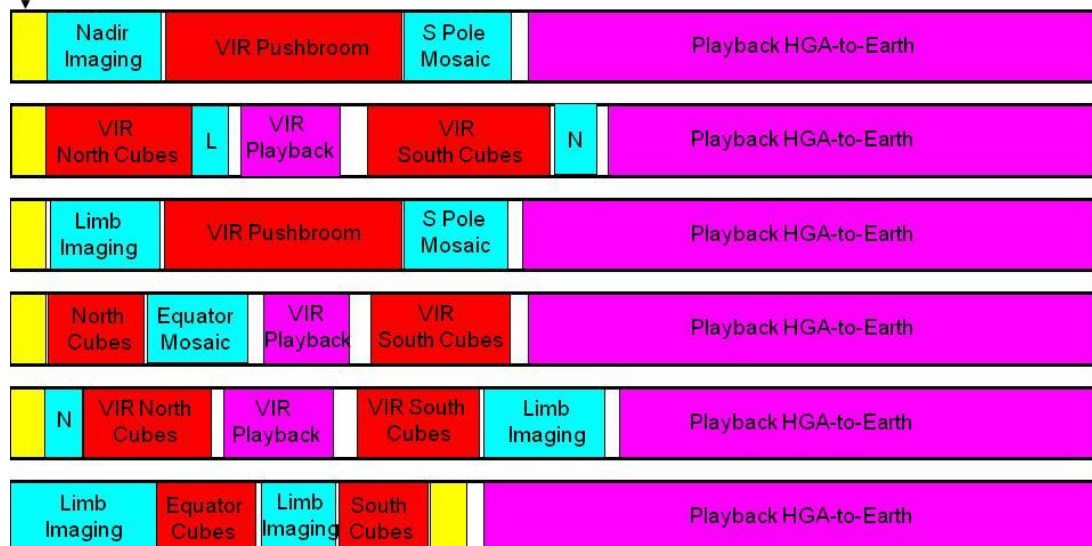
61



Survey Activity Overview

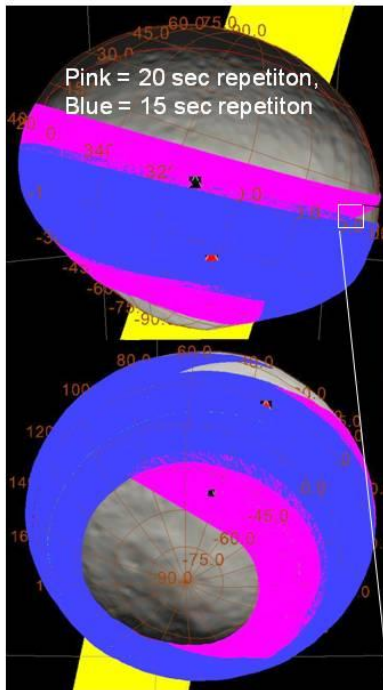


OpNav





Survey C1 and C3



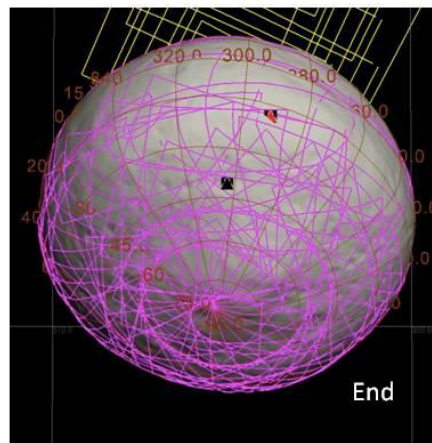
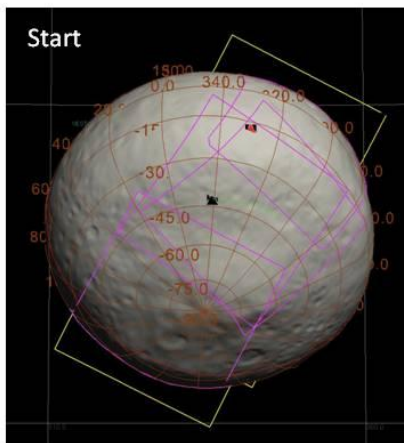
Views of the pushbroom mapping with VIR in C1 and C3 is shown at left

Begins at 5-15N and ends at 45-60S

- Gaps appear at the edges of the slits near the equator (below)



1x3 South Pole Mosaic - SOA





HAMO Constraints and Requirements

- Constraints
 - Onboard memory (VRs and Instruments)
 - Lighting conditions
 - Downlink only on darkside to enable global mapping (except for 2 orbits)
 - Accommodate other activities (orbit maintenance; opnav imaging)
- Variables
 - Off-nadir look angles
 - Downlink frequency
 - Number of FC filters per mapping
 - VIR acquisition strategy (cubes/targets/pushbroom)
- Satisfy the Level-1 requirements to:
 - **4a.** Obtain images of $\geq 80\%$ of the surface of Vesta with a sampling of ≤ 100 m per pixel, and a signal-to-noise ratio of at least 50, in the clear filter and in ≥ 3 color filters.
 - **5a.** Obtain a topographic map of $\geq 80\%$ of the surface of Vesta, with a horizontal spatial resolution of ≤ 100 m, and a vertical accuracy of ≤ 10 m.
 - **7a.** Measure and map the mineral composition of Vesta by obtaining ≥ 10000 high spectral resolution frames* from its surface at wavelengths between 0.25 and 5 microns with a spectral resolution of 2-10 nm. At least half of these spectral frames will be at a spatial resolution ≤ 200 m, and the remainder at a spatial resolution ≤ 800 m.

* A spectral frame is defined as a two dimensional array with a line of spatial pixels in one dimension and an array of spectral samples in the other dimension.

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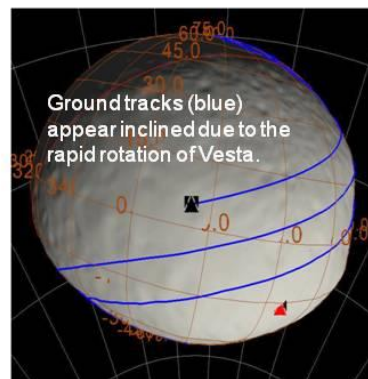
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HAMO-1 At-a-Glance



- Radius 950 km
- Trajectory: S2H2-002_smooth.bsp
- TOL: vsh_100216_S2H2-02_SCItol_b.xls
- Start Date: Sept 25, 2011
- 60 orbits
- Total number of FC images acquired:
 - 6158 (1.8 : 1 compression)
 - 2400 (5.4 : 1 compression)
 - 8558 total
- Total number of VIR frames acquired:
 - 72460 (1.8 : 1 compression)



Ground track sweeps out full 360 degrees of coverage in 10 orbits over 5 days, deemed one cycle

- No Dedicated Opnav imaging (use clear filter science images)
- Two 6-hr OMM windows after C2 & C4

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HAMO-1 Overview



- Plan Overview
 - 60 orbit plan: 6 cycles of 10 orbits (C1-C6)
 - Cycles 1 and 6 collect L-1 nadir data and are functionally redundant to ensure data receipt in case of a short safing, instrument issue, or transmission problem, but add synergistically to improve coverage and add robustness to the plan (image overlap, gap filling)
 - Some functional redundancy in off-nadir imaging cycles 2, 3, 4 and 5
 - Achieves the global image mosaics needed to map the geologic and cratering history of the body
 - Acquires the main off-nadir imaging data to enable topographic mapping via stereophotogrammetry and stereophotoclinometry
 - Collects high-resolution VIR data to map the composition and thermophysical evolution of the body

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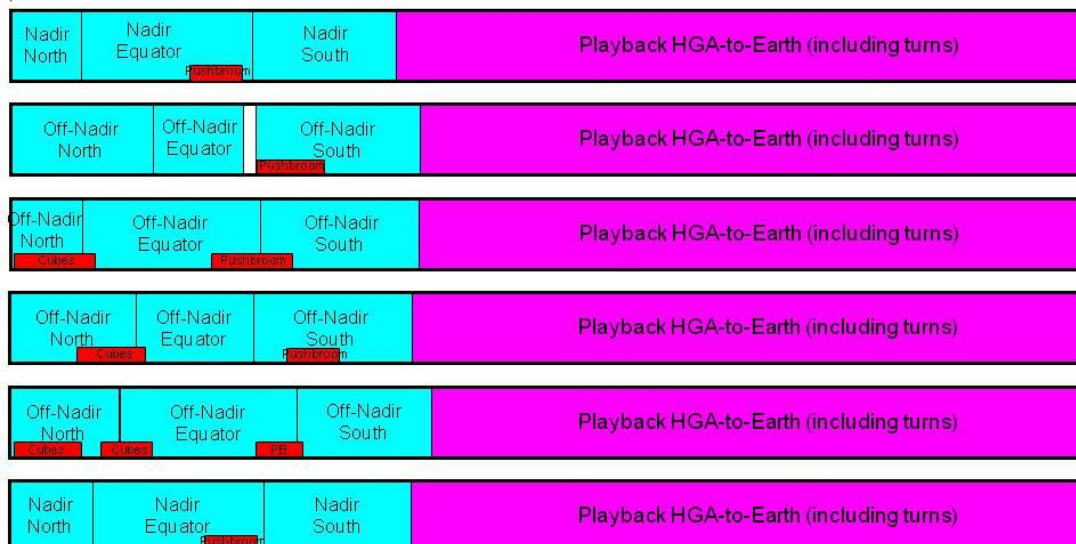


HAMO-1 Activity Overview



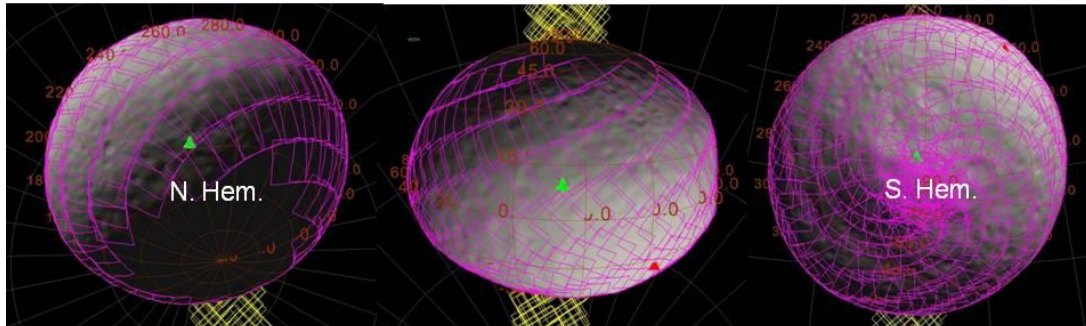
Imaging Start

(one example ~12-hour orbit per each 10-orbit Cycle)





FC Nadir Mapping in HAMO-1



Data compressed losslessly in clear and four color filters in Cycles 1 and 6

- Three remaining filters are lossy compressed 5.4:1
- All seven color filters collected losslessly between Cycles 1 and 6
- Ensures L-1 requirement is achieved while maximizing the science return

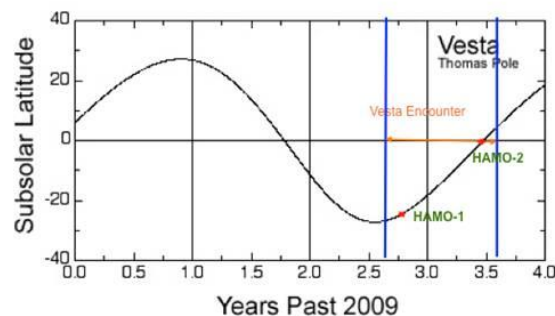
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HAMO-2 Overview

- Plan Overview
 - 40 orbit plan: 4 cycles of 10 orbits (C1-C6)
 - Cycles 1, 2, 3 collect off-nadir over entire body
 - Cycle 4 collects nadir and filter data in northern latitudes (last to get best illumination)



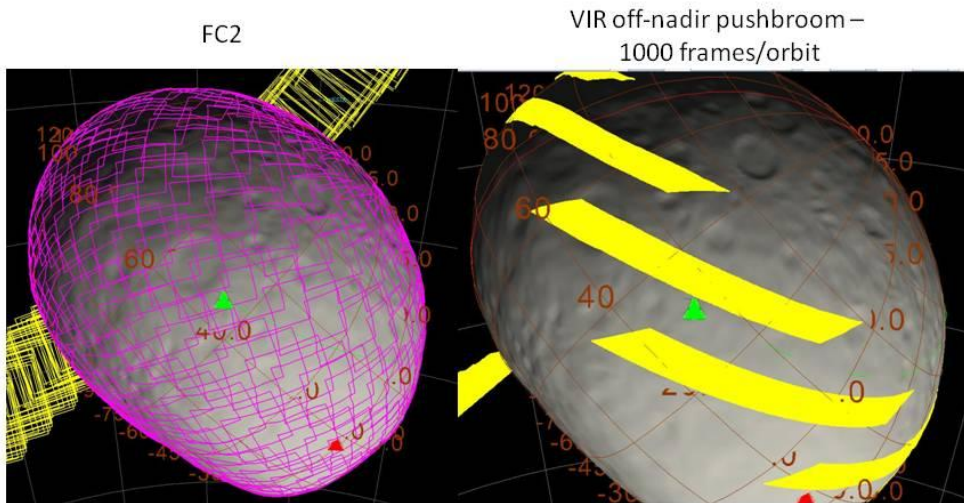
- For Thomas rotation pole, allows observation of previously unilluminated northern latitudes to more completely map the geologic and cratering history of the body, especially the antipode of the large south pole basin
- Acquires critical off-nadir imaging data to complete the topographic mapping via stereophotogrammetry and stereophotoclinometry

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HAMO-2 Cycle 1 – Ahead+8 Cross+5



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State of the Topography Investigation



- Loss of laser altimeter led to the plan to derive topography from image data
- L-1 requirement for Vesta is to obtain 80% coverage with 100-m spatial resolution and 10-m height accuracy (1-s)
- Compliance with this requirement has been difficult to demonstrate and has led to a significant effort to optimize the plan and prove the requirement can be met
 - Initial baseline plan relied on stereophotoclinometry (SPC), requiring cheby-based, variable off-nadir pointing to achieve maximum accuracy. Cheby-based pointing found to be problematic for Dawn ACS system. Constant illumination conditions in HAMO-1 not good for SPC.
 - Plan has evolved as processing techniques have improved, leading to a default **stereo** baseline using simple ACN pointing, with SPC as an alternate method

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State of Topography (Cont.)



- Achieving 80% coverage:
 - Addition of HAMO-2 ensures coverage requirement can be met assuming the current planning pole
 - New pole (Li et al., submitted) reduces coverage for the current plan and mission timeline and may require staying longer
- Achieving 10-m height accuracy:
 - Model simulations indicates height accuracy is achievable
 - Path to integrated topographic model has been identified and embraced by the various analysis team
 - Can achieve accuracy but not coverage in HAMO-1 with stereo only
 - Will achieve full requirement after HAMO-2 via multiple techniques

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Topography Plan



- Plan is to collect image data in three orbit subphases at different solar phase and beta angles to enable modeling using stereophotoclinometry (SPC) as well as stereophotogrammetry (stereo)
 - Survey: collect ~500 images with good phase angle coverage ($\beta=10^\circ$)
 - HAMO-1: Collect two nadir and four off-nadir global mappings ($\beta=30^\circ$)
- 2 off-nadir cycles 'optimized' for stereo
- 2 off-nadir cycles 'optimized' for SPC
- 1 view of each optimized set is useable by the other technique
 - HAMO-2: Collect one nadir and three off-nadir mappings ($\beta=45^\circ$)
- 3 off-nadir cycles optimized for stereo (data doesn't combine with HAMO-1 due to different illumination conditions)
- SPC benefits from different illumination conditions
- Addition of HAMO-2 is key to achieving topography requirement of 80% coverage with 100-m spatial resolution and 10-m height accuracy
 - LAMO: collect ~1300 'nadir' clear filter images

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HAMO Observing Geometry



HAMO-1 Observation Geometry

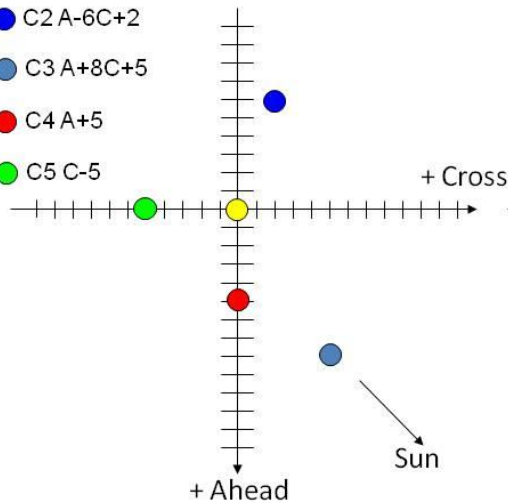
● C1/C6 Nadir

● C2 A-6C+2

● C3 A+8C+5

● C4 A+5

● C5 C-5



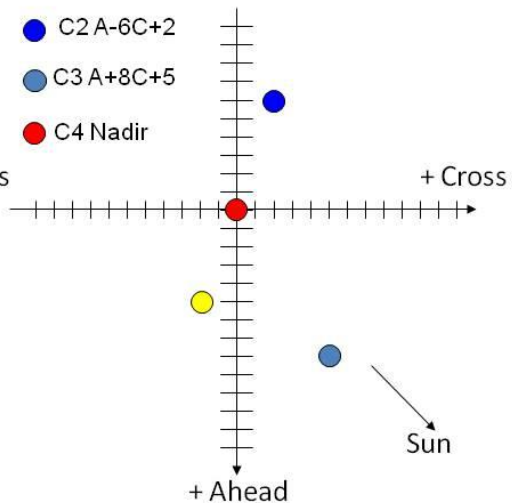
HAMO-2 Observation Geometry

● C1 A+5C-2

● C2 A-6C+2

● C3 A+8C+5

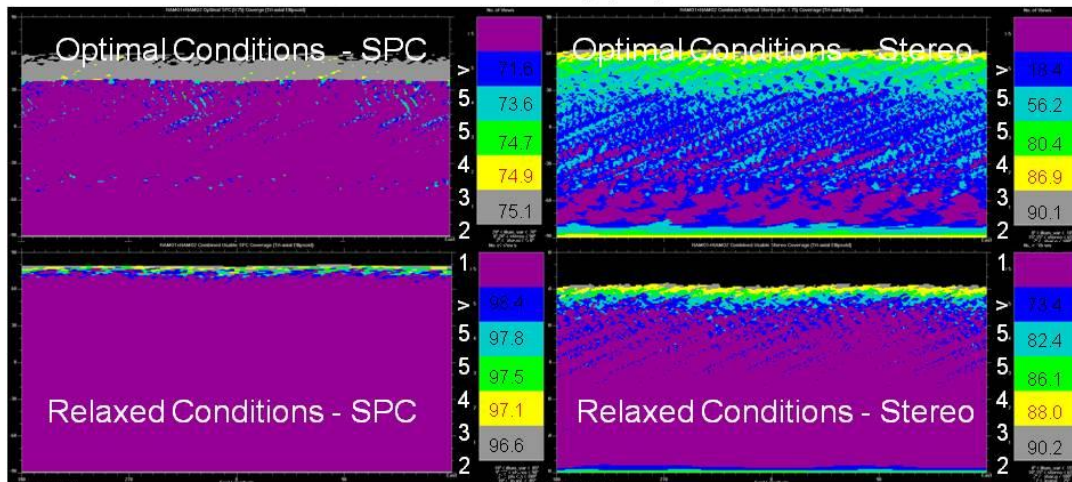
● C4 Nadir



Results of Combined H1 & H2 Coverage Analyses



- 80% body coverage is met for either stereo (right) or SPC (left)
 - 3 views (green) is requirement; 4 views shown in teal; 5 views shown in blue; > 5 views shown by purple





Validation of Topography Plan: Virtual Vesta



- Simulated Vesta images were produced from a 10-m height accuracy truth model sampled with expected noise, according to the original HAMO-1 observation plan (3 off-nadir cycles @ 900 km radius)
- Images were analyzed to verify procedures for shape & topography determination and to quantify expected errors
- PSI produced the result for SPC, and DLR produced the result for stereo
- Model results were compared to the truth model to determine expected height accuracy

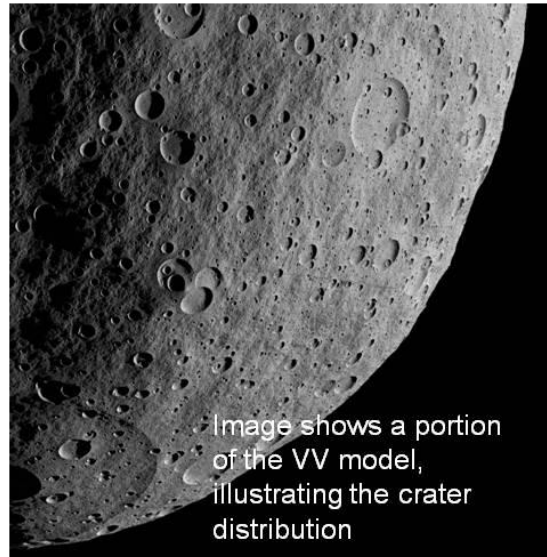
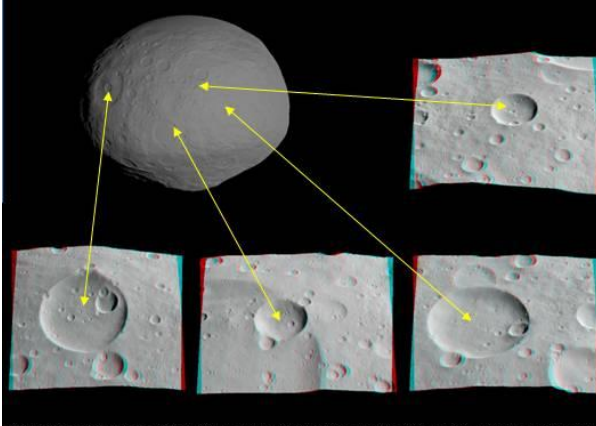


Image shows a portion of the VV model, illustrating the crater distribution

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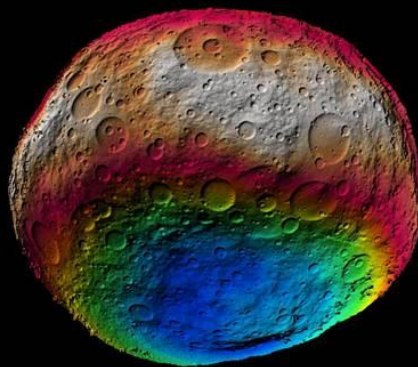
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Virtual Vesta Results



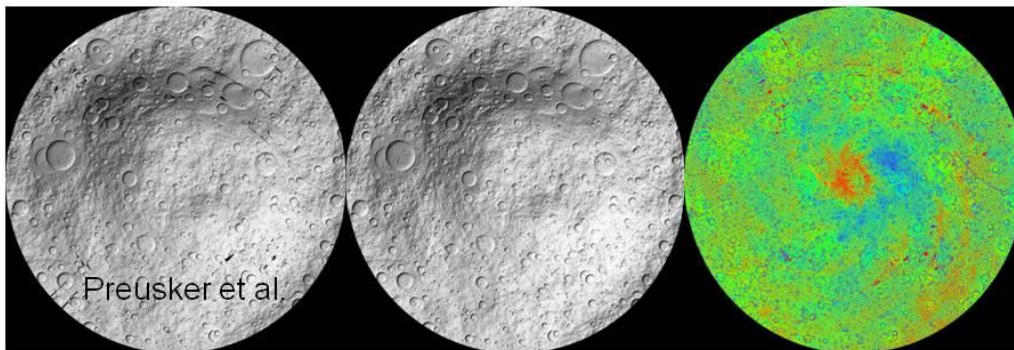
- SPC DTMs extend to ~50° north
 - 387 DTMs, 513x513 at 100 m/pixel
 - 136 DTMs, 513x513 at 50 m/pixel for test area
 - RMS height error of 119 m
 - Relative RMS height error of 116 m

- Stereo DTM extends to 47°N (87% of surface)
 - 125 m raster DTM product
 - DTM from 2.7 Billion points
 - Mean point accuracy: 6.0 m(3D, 1 sigma, 6.0 == 0.1 pixel)





Comparison of Stereo DTM to truth model



Statistics for DTM 0-90S lat:

-30 m  30 m

- ~80 % coverage within +/- 30m absolute height error
- ~95 % coverage within +/- 60m absolute height error

Remarks:

- small deformation of DLR model near and at south pole
- artifacts in truth model

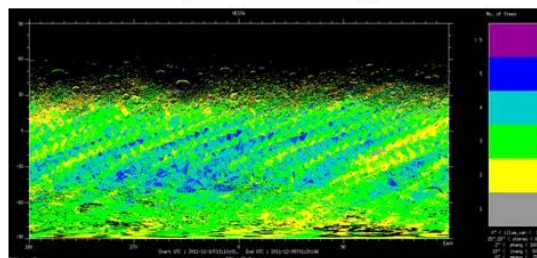


Scaling Stereo VV Results to Current Plan



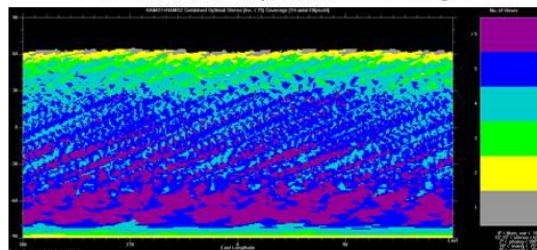
VV Optimal Coverage

- VV 3-cycle plan had 57.6% coverage at optimal conditions



Current Plan Optimal Coverage

- Current 4-cycle H1/H2 plan has 87% coverage with optimal stereo conditions
 - Implies height accuracy will be better than the VV simulation



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Topography Analysis Methods



Method	Institution	Persons	Products	Software/Tools/ Platforms	Data formats
SPC	PSI	R. Gaskell	Maplets - topo and albedo	Mapmaker - generate custom products from maps and maplets	PDS Products for shape model, maps (DTK)
		L. Jorda	99x99 px		
		N. Mastrodemos	Global Topo Model - GTM@800m		
			Maps @50m res 1025x1025		
			Control Pts - 250K	Ames Supercomputer	Control pts as body-fixed vector; pixel, line coord. in image
			Covariance Matrices		
Refined PC	LAM-France TUBS-IGEP	L. Jorda	Global Shape Model (SHM)	Error Modeling Tool	Spherical Harm. Shape
		U. Keller	(from Approach/Survey data)		
			Quantitative error maps - photon noise and slopes		
			Refined photometric model (post-HAMO)		
			Refined topo @ map-scale (hi-res - post-HAMO)		SPC derivative maps
Stereo	DLR	F. Preusker	Shape Model (post-Survey)		PDS Products for shape model, maps (DTK)
		F. Sholten	DTMs @ ~100m res (post-HAMO)		
		T. Roatsch	hi-res local DTMs		
			Mosaic w/monochrome		
			Cartographic maps		
			control pt network/improved orbit and ptg		

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Reference Network



- GEODYN (GSFC Tool) will be used to merge radiometric data with image-derived heights to produce a topographic model referenced to Vesta center-of-mass
- Input to Geodyn:
 - shape models
 - controls pts
 - orbits and ptg - SPK, CK
 - DTM @ various resolutions
 - error models
- Produce reference control point network at increasing resolution during Vesta encounter

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Topography Workflow



Survey	HAMO	Post-HAMO	mid-LAMO	Post-HAMO2	Post-Vesta	
Global Shape and control pts		1st iteration of image-derived topo models	2nd iteration of image control pt network (Npts)	2nd iteration of image-derived topo models	final shape model (Jan '13)	final topo model (Apr '13)
	low-order gravity model (L-4-6)	1st order reference network (36 pts)	gravity model to 12x12 (20x20)	2nd iteration of reference network (Npts)	Final gravity model 20x20 (26x26)	

- Need reconstructed orbit and pointing kernels (SPK, CK) for each major step
- Desire weekly deliveries of best-efforts kernels with official products at the major boundaries

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LAMO Plan Overview



- Sequence architecture
 - Science Plan is built in 1-week repeating Cycles of two varieties
 - Each Sequence contains 2 Cycles (background as well as science)
 - Nominal plan is 10 weeks (+2-6 days) with 3 weeks of possible growth
- Framework of Plan is illustrated below
 - One 7:45 HGA tracking pass every two days (3 passes per week) for 6 weeks and one 6:00 pass 3 times per week for the remaining 4 weeks
 - Desats monitored over HGA tracking passes (3 desats/wk days 1-6)
 - Continuous tracking achieved with LGA to both 70 m and 34 m stations
 - GRaND: total time at nadir is 1296 hours (78% duty cycle)
 - Gravity: total of 30 HGA tracking passes and 70 LGA-to-70m tracking passes
 - OpNav: C1-C6: 100 images per 2 days, C7-C10: 28 images per 2 days
 - FC2: clear filter mapping for 6 weeks followed by color filter mapping
 - VIR: data collected in on selected orbits

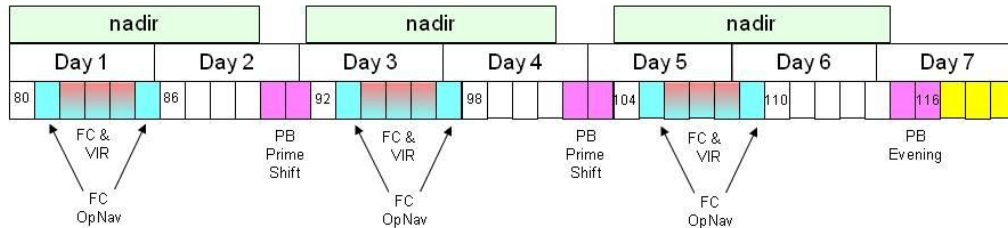
DSN HGAtracking 7:45, 3 times each week						DSN HGAtracking 6:00, 3 times each week					
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
FC2 clear filter only						clear every day + color (F2,F3,F4)				FC2 clear/2 days	
Sequence 1		Sequence 2		Sequence 3		Sequence 4		Sequence 5			



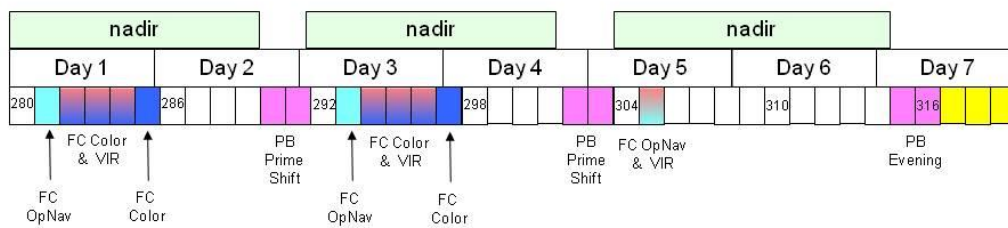
Schematic of LAMO Cycles



Example of 1-week Cycle from C1-C6: C3 – Orbits 80-119 (7hr 45 min HGA pass)



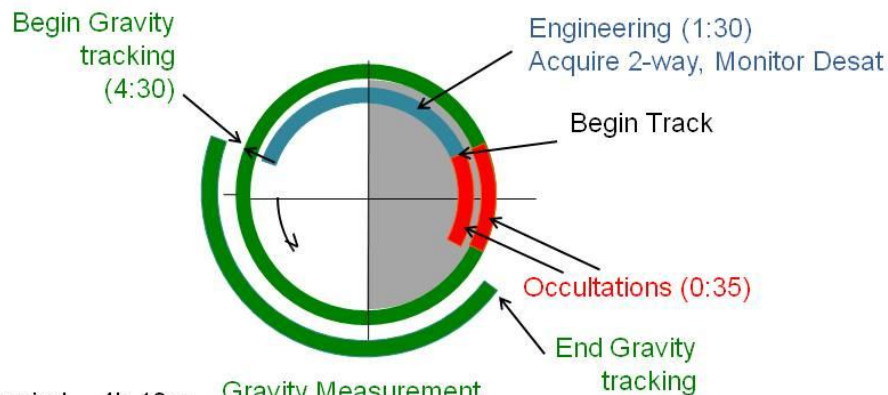
Example of 1-week Cycle from C7-C10: C8 – Orbits 280-319 (6 hr HGA pass)



Note: Orbits are shaded to indicate activities even though the activities don't necessarily fill the whole orbit



LAMO Gravity HGA 7:45 Example



Orbit period ~ 4h 10m

Gravity Measurement

Downlink pass begins at occultation end

90 minutes of tracking before gravity tracking to:

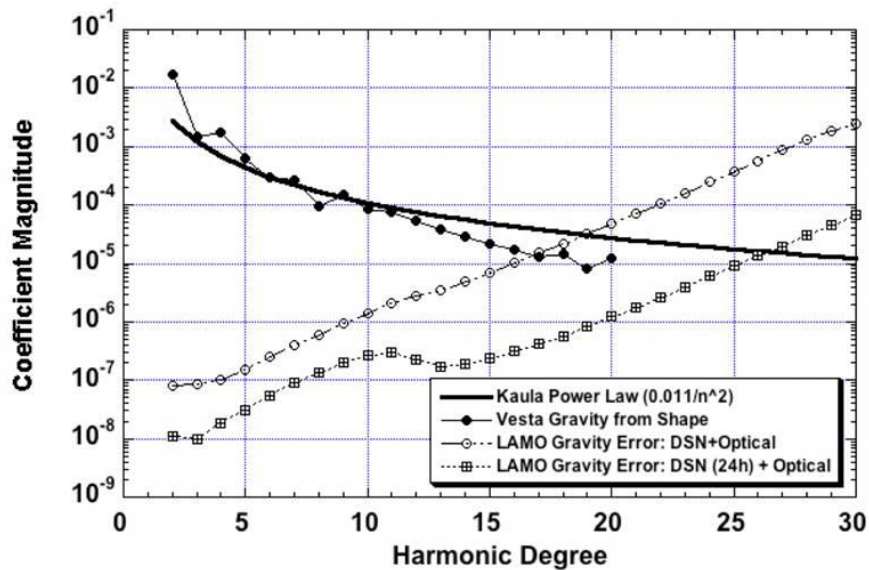
- establish 2-way tracking
- monitor desat (likely to be on order of 15 min)

6 hr 5 min gravity pass – desire to maximize equatorial coverage

- gravity pass will contain another occultation



Expected Gravity Results



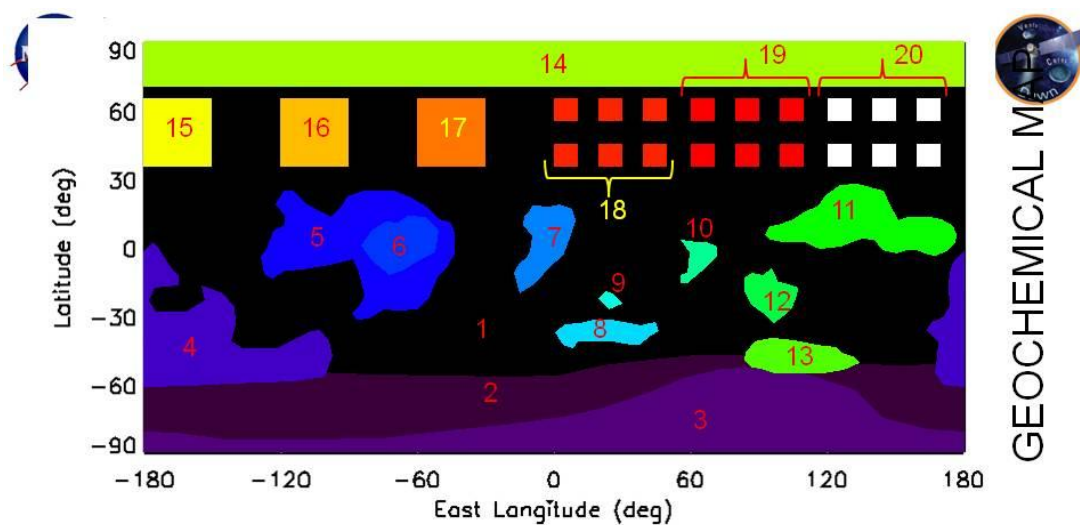
Exceeds requirement by more than a factor of 2



Assessing the GRaND Plan: Geochemical Virtual Vesta

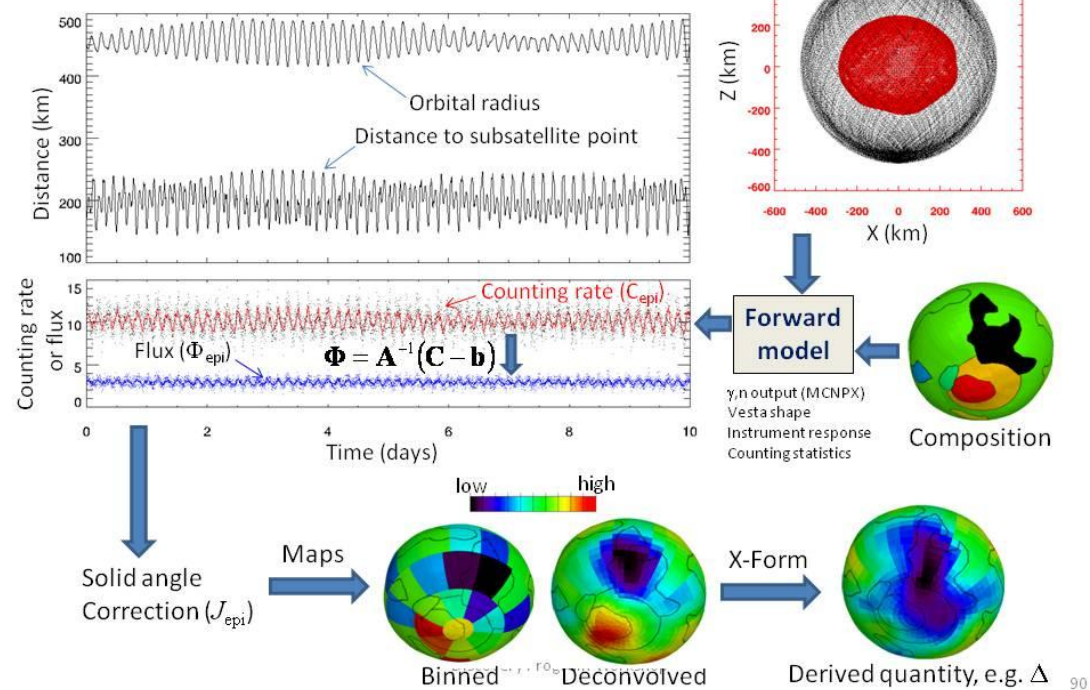


- Carry out end-to-end simulations of the response of GRaND at Vesta
 - Composition scenarios (HED systematics, maps based on HST imagery)
 - Realistic treatment of orbit-dynamics and counting statistics
 - Instrument calibration, output/response calculations, characterization of backgrounds,
- Use simulations to assess different operational scenarios
 - Means of communicating the impact of mission operations on science
 - Mean of assessing the sensitivity of GRaND to a hypothesis (e.g. minimum detection limits for K?)
 - Can GRaND determine olivine composition?
- Develop data reduction/analysis procedures
 - Means of determining what questions can be answered and what tools and data products are needed;
 - and how GRaND data would be used in combination with other data sets



1. Howardite or polymict eucrite	48 <BE>:<D>=2:1	11. Low-Ca Eucrite (III)	23 CE Serra de Magé
2. VSPC outer	11 D Shalka	12. Weathered materials (VI)	24 CE Serra de Magé
3. VSPC inner	44 Olivine, Fo71	13. Low-Ca Eucrite (III)	22 CE Moore County
4. Diogenite (IV)	19 D Tatahouine	14. Variable K	48 <BE>:<D>=2:1
5. Eucrite (II)	25 CE Y-791195 ,75	15. Variable K	48 <BE>:<D>=2:1
6. Eucrite	31 BE Pasamonte	16. Variable K	48 <BE>:<D>=2:1
7. Eucrite (II)	41 BE Lakangaon B	17. Variable K	48 <BE>:<D>=2:1
8. Fresh surface (V)	36 BE Haraiya	18. Diogenite	17 D Ibbenbühren
9. Diogenite (IV)	15 D Type B, Y-791199 ,79	19. Diogenite	16 D Elmeeth
10. Diogenite (IV)	16 D Elmeeth Discovery Project	20. Diogenite	15 D Type B, Y-791199 ,79

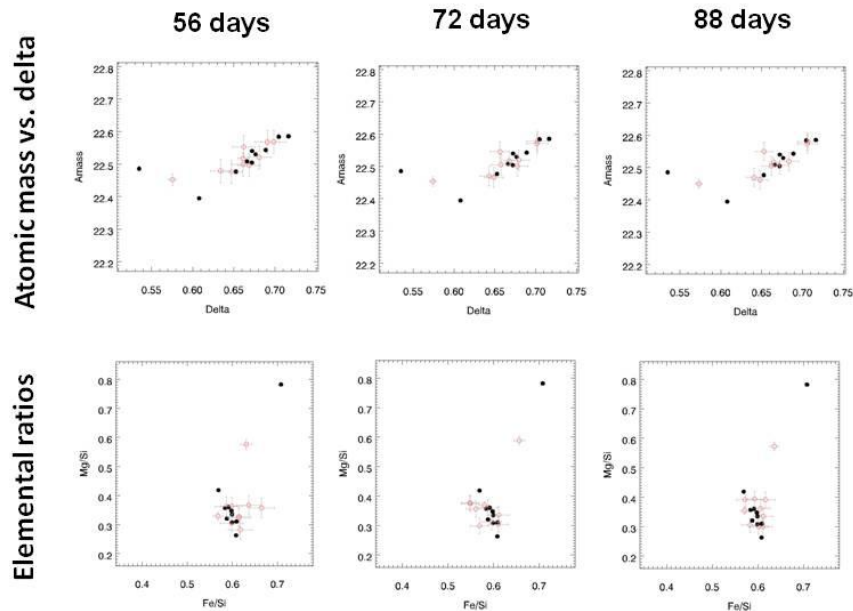
NASA Mapping Simulations





Nominal LAMO Scenarios

90° equal area maps



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Targeted Observations



- Limited in number and late in subphases/encounter
- Two general categories:
 - Adjustments to timing of observations within planned activities
 - Changes in cadence
 - Bunching or spreading observations
 - Moving cubes
 - Targets of Opportunity
 - Example: Imaging while slewing to Earth



Data Analysis and Archiving



Data Product Production and Archiving Schedule



Instrument	Data Product	Provider	Mars	Vesta	Ceres
Spacecraft (Ground Segment)	Predict SPK kernels	NAIF	End of Data Acquisition (EDA)	EDA	EDA
	Predict CK kernels	NAIF	EDA	EDA	EDA
	Reconstructed SPK	NAIF	Departure (D)	D	D
	Reconstructed CK	NAIF	D + 1 month (m)	D + 1 m	EOO + 1 m
	Uplink products	DSC	D + 1 m	D + 1 m	D + 1 m
	S/C engineering	DSC	D + 1 m	D + 1 m	D + 1 m
GRaND (T. Prettyman)	Ancillary data	DSC	D + 1 m	D + 1 m	D + 1 m
	Level 0	DSC	EDA	EDA	EOO
	Level 1a	DSC	EDA + 3 m	EDA + 3 m	EDA + 1 m
	Level 1b	GRaND	D + 6 m	D + 6 m	EOO + 3 m
Framing Camera (A. Nathues)	Level 2	GRaND	D + 12 m	D + 12 m	EOO + 5 m
	Level 0	DSC	EDA	EDA	EOO
	Level 1a	DSC	EDA + 3 m	EDA + 3 m	EDA + 1 m
	Level 1b	FC	D + 6 m	D + 6 m	EOO + 3 m
VIR (A. Coradini)	Level 2	FC	D + 12 m	D + 12 m	EOO + 5 m
	Level 0	DSC	EDA	EDA	EOO
	Level 1a	DSC	EDA + 3 m	EDA + 3 m	EDA + 1 m
	Level 1b	VIR	D + 6 m	D + 6 m	EOO + 3 m
Gravity Science (A. Konopliv)	Level 2	VIR	D + 12 m	D + 12 m	EOO + 5 m
	Level 0	GS		D	EOO
	Level 2	GS		D + 6 m	EOO + 6 m



Higher Level Data Products



Instrument	Data Product	Level	Mars	Vesta	Ceres
GRaND	Gridded count rate data	2		D + 12 m	EOO + 6 m
	K/Th/U Maps	3		D + 18 m	EOO + 6m
	Si Map			D + 18 m	EOO + 6m
	Ca Map	3		D + 18 m	EOO + 6m
	Al Map	3		D + 18 m	EOO + 6m
	Fe Map	3		D + 18 m	EOO + 6m
	Mg/Ti Map	3		D + 18 m	EOO + 6m
	H Map	3		D + 18 m	EOO + 6m
Framing Camera	Geometrically corrected data	2	D + 12 m	D + 12 m	EOO + 6 m
	Global clear atlas	3		D + 18 m	EOO + 6m
	Global color atlas	3		D + 18 m	EOO + 6m
	Global mosaic	3		D + 18 m	EOO + 6m
	Topographical model	4		D + 24 m	EOO + 6m
VIR	Geometrically corrected data	2	D + 12 m	D + 12 m	EOO + 6 m
	Pyroxene map	3		D + 24 m	EOO + 6m
	Olivine map	3		D + 24 m	EOO + 6m
	Geological map	4		D + 24 m	EOO + 6m
Gravity Science	Grav. Coeff. and Covar.	2		D + 6 m	EOO + 6 m
	Free air gravity map	3		D + 12 m	EOO + 6m
	Geoid and uncert. map	3		D + 12 m	EOO + 6m
	Bouguer map	4		D + 12 m	EOO + 6m



Replanning/Transition Criteria



Mission Replanning



- Science Planning has focused on dealing with uncertainty
 - Relative-timed mapping sequences are robust and adaptable to time shifts and geometric (orbit) perturbations
 - Waypoint strategy starts and ends each turn at nadir to allow activities to move without leaving spacecraft in unknown attitude
 - Result is that sequences can be moved around, truncated, or restarted without major impacts
- Because Dawn must leave Vesta at a certain point, we must manage the time and it is important to stay on the plan
 - Dawn has developed transition criteria to assess and manage the progress against the plan

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What Are Transition Criteria?



- Transition criteria are criteria that must be met before the mission progresses from one sub-phase to the next
 - Sub-phases: Approach, Survey, HAMO, LAMO, HAMO2, Departure and all the transfers in-between
- Transition criteria are assessed and reported on by the relevant teams using checklists and presentation formats that have been reviewed by the project
 - These assessments are given during 1-hour Transition Criteria meetings
 - These meetings are scheduled days in advance of the upcoming sequence upload/execution periods
- The transition criteria were designed to check that we:
 - (For science orbit entrances) have delivered the flight system to an orbit which meets the science orbit requirements
 - (For science orbit departures) have collected data that meet the Level 1 requirements expected from the sub-phase we are leaving as well as data required for navigation
 - (For nominal operations) have a correctly configured mission and flight system, have approved sequences, and have designed safe transfers that will achieve the next science orbit

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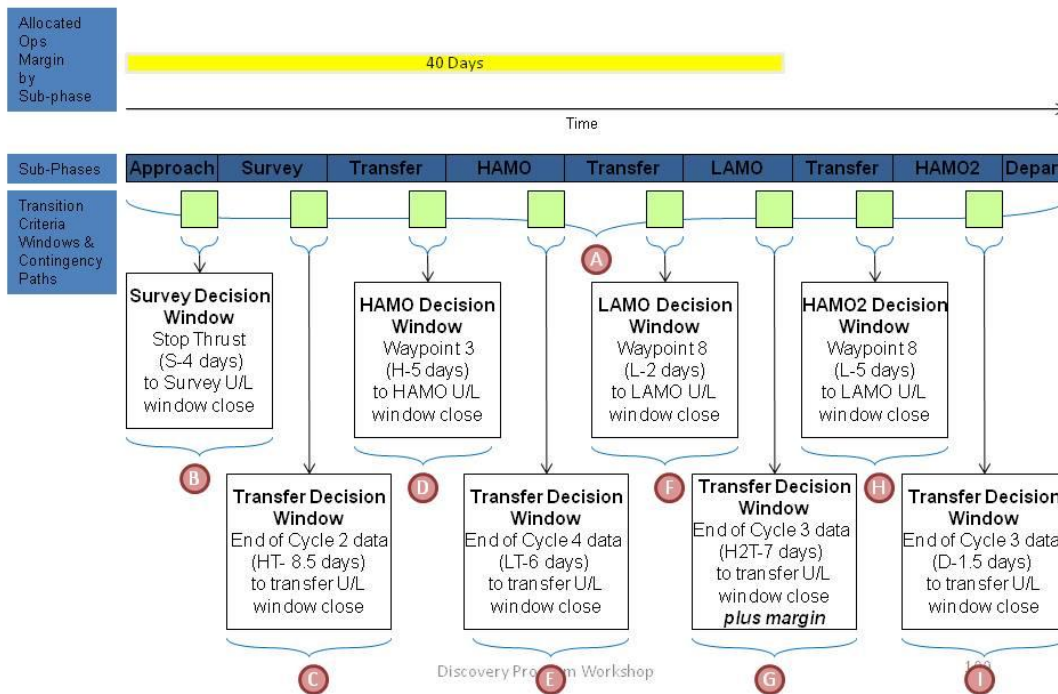
Why Do We Need Transition Criteria?



- Good news: Most of the science sub-phases are designed to collect functionally redundant data and are designed to far exceed the amount of data needed to satisfy the Level 1 requirements
 - We also have 40 days of operations margin set aside to extend sub-phases when required due to anomalies or surprises
- However, we have a constrained mission duration at Vesta in order to meet a programmatic constraint to arrive at Ceres by Feb. 2015, so there will be pressure to stay on plan
 - In order to get to Ceres on time, we need to leave Vesta on time
 - There is no appreciable margin in the Vesta to Ceres transfer to allow for a later Vesta departure under these guidelines
 - Lingering beyond the planned duration of any sub-phase will risk data collection in later sub-phases
- We don't want to leave a sub-phase without making sure that we have collected the required data
 - We need to avoid confusion and real-time debate over what data are required vs. desired
- Thus, we devised pre-established and agreed-to criteria and procedure by which we make transition decisions
 - Caveat: we cannot possibly anticipate every situation, so waivers can be considered



Transition Criteria/Contingency Overview Timeline

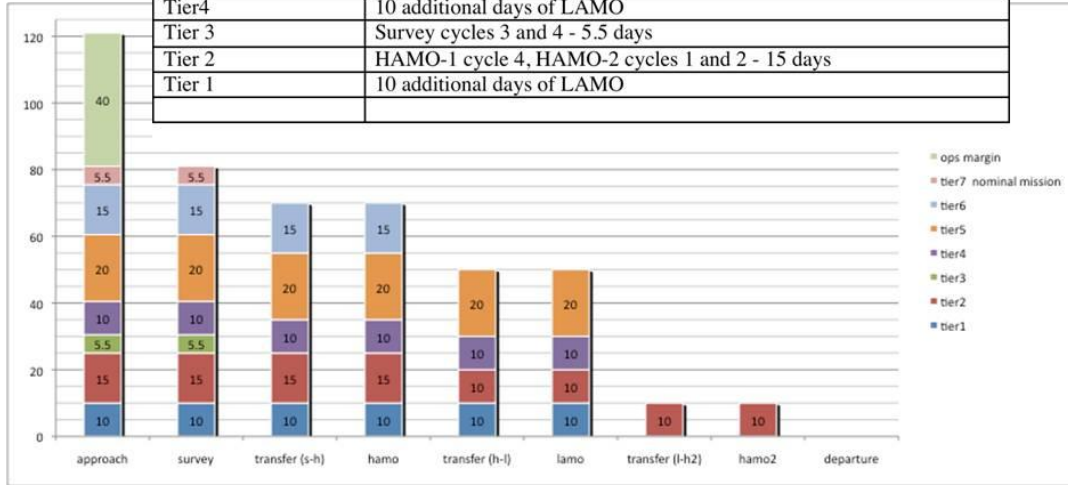




Contingency Descope Plan



Tier	What is removed
Ops Margin	Nothing - nominally 40 days of margin
Tier7	Survey Cycles 5 and 6 - 5.5 days
Tier6	HAMO-1 Cycles 5 and 6, HAMO-2 Cycle 3 - 15 days
Tier5	20 days of LAMO
Tier4	10 additional days of LAMO
Tier 3	Survey cycles 3 and 4 - 5.5 days
Tier 2	HAMO-1 cycle 4, HAMO-2 cycles 1 and 2 - 15 days
Tier 1	10 additional days of LAMO



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Wisdom



- Make the best decisions possible with the information you have
 - Don't wait until you know everything
 - Look for ways to work around obstacles and uncertainty
 - Don't polish the cannonball....
- Simple can be elegant...and understandable
- Optimize the big picture first
 - Write good requirements
 - Establish clear priorities
- Communicate clearly and follow-through
- Capitalize on the strengths of the team and work around the weaknesses

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